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The Effects of Noise on Aquatic Life II

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Preface

This book presents the papers presented at the Third International Conference on the Effects of Noise on Aquatic Life that took place in August 2013 in Budapest, Hungary. The meeting, like its predecessors in Nyborg, Denmark (2007; Hawkins et al. 2008), and Cork, Ireland (2010; Popper and Hawkins 2012), introduced participants to the most recent research on the effects of man-made noise on aquatic animals and the aquatic environment. Almost 250 scientists, acousticians, engineers, regulators, and representatives of industry and environmental groups from 24 countries came together to share data and ideas and to meet colleagues with interests across the range of topics covered at the meeting. The effects of noise on a wide range of animals were discussed and debated over the 5 days of the conference, as were issues related to different sound sources, national and international regulations, and the interests of industrial and environmental groups. The animals considered included marine mammals, turtles, amphibians, fishes, and invertebrates.

The various themes of the meeting were chosen to cover the principal subjects of current interest. They included the hearing abilities of aquatic animals; communication by means of underwater sound; the description of aquatic soundscapes; different sound sources and their characteristics; the effects of sound on behavior; and assessing, mitigating, and monitoring the effects of aquatic noise. There is now increasing interest by the general public in the impact of underwater noise, while there is a continuing requirement for governments and industry to conduct formal assessments of the impact of offshore developments. As a consequence, special panels (see the Chapters 159 by Erbe et al., 160 by Johnson and Dolan, 161 by Lewankowski et al., and 162 by Scowcroft) were convened to discuss two especially relevant topics: ways of communicating the results of science to the general public and how best to facilitate closer interaction between regulators and those being regulated.

Papers were submitted by a large number of participants and this generated a very full program. The idea previously tested in Nyborg and Cork of having several sessions of short, rapid-fire presentations about various posters was further developed and proved a great success. The rapid-fire talks added value to the large number of poster presentations and allowed their presenters to draw attention to the wide range of new studies of underwater noise and its effects.

Since the original Nyborg meeting, there has been an enormous increase of interest in underwater noise. The development of offshore renewable energy resources, dredging for aggregates, construction activities, the use of sonars, increases in commercial shipping, and the further development of the offshore oil and gas industry have led to increasing work by scientists and engineers on the effects of this noise. Our three conferences have brought together a whole community of people engaged in work on underwater noise and have enabled a very full exchange of ideas to take place. Many people are now looking forward to the next conference, to be held in 2016 in Dublin.

Finally, a note about the "organization" of this book. From looking over the various chapters, it is clear that they could have been organized any number of ways. This could have been, for example, based on animal groups, sound sources, experimental approaches, and other ways. Since we could not come up with a scheme that we thought would satisfy everyone (or even ourselves), we took the approach that we would present the papers in alphabetical order of the first author, and then let readers either browse the volume or do electronic searches on the PDF or electronic versions of the volume. This decision is, of course, based in part that most people will view the book in electronic form, as is so often the case for new books today.

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Anthony Hawkins, Aberdeen, UK

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The editors and organizers would also like to express their gratitude to the large number of people who provided help in planning and executing the meeting.

We start with our wives, Susan Hawkins and Helen A. Popper, for substantial and invaluable guidance in selecting the meeting site and planning the non-science activities for the meeting.

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Co-Organizers
Christine Erbe, Australia
James Miller, USA
Joseph Sisneros, USA

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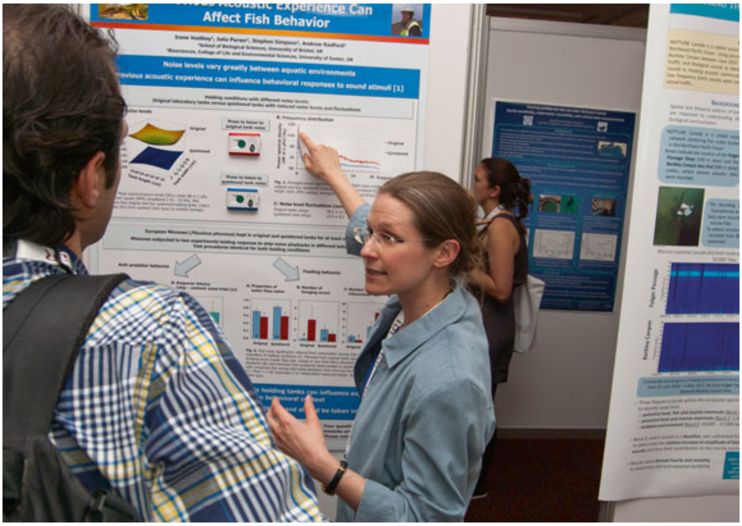
Meeting session in grand ballroom of Corinthia Hotel

Networking

The organizers, Art Popper and Tony Hawkins



Poster session

Michael Ainslie

Sharing data

Rob McCauley and co-organizer Christine Erbe

A break to sightsee on the Danube

Conversation before dinner

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Chapter 1
Noise-Induced Hearing Loss: Permanent Versus Temporary Threshold Shifts and the Effects of Hair Cell Versus Neuronal Degeneration

M. Charles Liberman

Abstract For decades, research on permanent noise-induced hearing loss has concentrated on the death of sensory hair cells and the associated threshold elevations. Recent work has shown that cochlear neurons are actually more vulnerable to noise, and even after exposures causing only temporary threshold elevation and no loss of hair cells, there is a rapid and irreversible loss of synaptic connections between cochlear neurons and hair cells followed by a slow degeneration of cochlear nerve cell bodies and central axons. Although this noise-induced neuropathy does not affect the audiogram, it likely reduces performance on more complex auditory tasks such as speech discrimination in noise.

Keywords Neuropathy • Cochlear nerve • Noise exposure

1 Measuring Noise-Induced Hearing Loss

It has been known for centuries that acoustic overexposure can cause permanent hearing deficits. Research on animal models and on autopsy materials from humans has shown that noise exposure can cause damage to many structures in the middle and inner ears. At very high sound pressure levels and short durations, such as those associated with bomb blasts, the eardrum can be ruptured (Kerr and Byrne 1975) and the entire sensory epithelium of the inner ear (cochlea) can be instantly lifted from its cellular moorings and left floating in the inner ear fluids (Hamernik et al. 1984), causing immediate and permanent deafness. At more moderate sound pressure levels and long durations, such as those associated with a noisy factory, there is no

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obvious damage to the middle ear; rather, there is an ongoing degeneration of the inner ear's sensory cells, the inner and outer hair cells, as well as of the fibers of the cochlear nerve that carry information from the sensory cells to the brain (e.g., Clark et al. 1987). Because these sensory cells and neurons never regenerate, at least in the mammalian inner ear, the hearing deficits that this degeneration causes are permanent and progressive with increasing exposure time.

Over the last 40 years, many groups have attempted to describe the functionally important structural changes underlying noise-induced hearing loss (NIHL) in animal models. The classic functional measure of NIHL is the auditory threshold. In humans, this is typically assessed via an audiogram, i.e., a measure of the lowest sound pressure level required at each test frequency to elicit an auditory percept. Although behavioral audiograms can be measured in animals (Miller et al. 1963), it requires sophistication in animal behavior and a significant investment of time in training each animal to respond. Thus, in animal work on NIHL, most investigators use minimally invasive physiological measures such as the auditory brainstem response (ABR) or otoacoustic emissions (OAEs). The ABR is measured using subcutaneous needle electrodes in the scalp. In response to short tone bursts and with a few minutes of signal averaging, the summed activity of the cochlear nerve fibers can be recorded from an anesthetized animal in response to tone bursts at different frequencies (Melcher and Kiang 1996), and the "threshold" can be estimated as the minimum sound pressure required to elicit an electrical response of a criterion magnitude. Cochlear thresholds can also be measured via OAEs, which are mechanical disturbances created by sound-induced motion of the hair cells in the normal cochlea that are transmitted back into the ear canal where they can be measured, as an objective sound, with a sensitive microphone (Kemp 2002). Measuring both OAEs and ABRs allows a differential diagnosis at the site of an inner ear lesion. When the hair cells are damaged, both OAEs and ABRs are attenuated; if only the ABRs are attenuated, it suggests that the hair cells are intact but that the nerve fibers are damaged. In audiology clinics, this condition is referred to as auditory neuropathy (Santarelli et al. 2009).

2 Permanent Hair Cell Damage and Noise-Induced Threshold Elevation

The classic structural metric of inner ear damage is the cytocochleogram, a count of hair cell loss as a function of position along the cochlear duct. The sensory epithelium of the mammalian inner ear spirals for several millimeters (35 mm in the human) from the cochlear base, where it is mechanically tuned to high frequencies, to the cochlear apex, where it is tuned to low frequencies (Schuknecht 1993). Because the normal mammalian pattern of three rows of outer hair cells and one row of inner hair cells is a perfect hexagonal lattice, it is easy to unambiguously determine the number of missing cells. Because cochlear maps (the relationship between cochlear location and frequency) are known for many mammalian ears (Liberman 1982a; Muller et al. 2005), the cytocochleogram can be expressed as fractional hair cell loss (or damage) versus frequency.

After a controlled noise exposure in the laboratory, the threshold elevation can be seen immediately after noise offset, and threshold recovery can continue, with a roughly exponential time course, for as long as 2–3 weeks (Miller et al. 1963). Any residual threshold shift after a few weeks is considered permanent. Research from numerous laboratories over several decades has shown that permanent noise-induced threshold shift as a function of frequency is well explained by the pattern of hair cell loss or damage as a function of cochlear location (Liberman and Dodds 1984). Outer hair cells are significantly more vulnerable to noise than inner hair cells (Liberman and Kiang 1978). Because outer hair cells are the “cochlear amplifier,” i.e., they transduce mechanical vibration into electrical signals and then use the electrical signals to drive an electromotile force that enhances the sound-induced vibration of the sensory epithelium (Dallos 2008), their loss alone can raise thresholds by as much 50 dB (Dallos and Harris 1978). Even if hair cells survive the exposure, their stereocilia are often badly damaged (Robertson et al. 1980). Because the stereocilia (or hair bundles) are the site of the hair cell’s mechanoelectric transduction apparatus, it is not surprising that stereocilia damage can also cause significant, and even profound, threshold elevation. Noise-induced stereocilia damage can also be permanent (Liberman and Dodds 1984).

Depending on the severity of the noise exposure, the threshold elevation seen immediately postexposure will sometimes recover completely to preexposure levels. Acute threshold elevation of as much as 50–60 dB, if measured immediately postexposure, can completely recover over 3–7 days (Miller et al. 1963). This type of temporary, i.e., reversible, noise-induced threshold shift looks very different under the microscope. Even if examined at peak threshold shift, i.e., immediately postexposure, there is no hair cell loss and no obvious stereocilia damage (Liberman and Mulroy 1982). There may be a reversible collapse of some of the supporting cells of the sensory epithelium (Wang et al. 2002), and there may be subtle submicroscopic damage to the rootlets anchoring the hair bundles into the tops of the hair cells (Liberman and Dodds 1987). There may be a host of other submicroscopic changes to the inner ear structures, but the nature of the most functionally important structural changes underlying temporary threshold shifts is quite poorly understood.

If the sensory cells look normal and if the thresholds have returned to normal, it has long been assumed that exposures causing a temporary threshold shift are completely benign. Recent research in my laboratory, discussed in Section 3, shows that this is definitely not the case.

3 Permanent Neural Damage after Temporary Threshold Shift

Although hair cell loss can be obvious within a day after a noise exposure, classical studies of noise damage reported that the loss of cochlear nerve fibers was not seen until weeks or even months postexposure (Johnsson 1974; Liberman and Kiang 1978; Bohne and Harding 2000). This offset in the time course of degeneration led to the conclusion that hair cell damage was the "primary" effect of the noise exposure and that the loss of cochlear nerve fibers was a "secondary degeneration," occurring only because of the loss of trophic-factor support supplied by the hair cells.

In assessing neural loss, investigators classically counted the cell bodies of the cochlear nerve fibers, i.e., the spiral ganglion cells, because they are easy to see in routine histological material assessed with a light microscope. Each cochlear nerve fiber makes synaptic contact with a single inner hair cell via a single unmyelinated terminal at the end of the peripheral axon extending from the spiral ganglion cell to the sensory epithelium (Liberman 1982b). These unmyelinated nerve terminals are classically studied with an electron microscope (Liberman 1980), and electron microscopists in the 1980s noted that if examined within roughly 24 h after noise exposure, ears with temporary noise-induced threshold shift showed a dramatic swelling of the postsynaptic terminals of cochlear nerve fibers in the synaptic zone underneath the inner hair cells (Liberman and Mulroy 1982; Robertson 1983). This swelling could be mimicked by perfusing the cochlea with glutamate agonists and blocked, at least partially, during acoustic exposure by cochlear perfusion with glutamate antagonists (Pujol and Puel 1999). Thus, there appeared to be a type of glutamate excitotoxicity because glutamate is the neurotransmitter at the hair cell synapses (Matsubara et al. 1996). Because the threshold shift in these ears was reversible, the swollen terminals were not seen when the ears were examined a few days postexposure, and no loss of ganglion cells was observed a few weeks postexposure, it was assumed that this neural damage was fully reversible, either via recovery or regeneration. However, quantification of the synapses is difficult with an electron microscope; thus, quantification was never carried out.

Elucidation of some of the molecular components of the hair cell's synaptic machinery enabled the development of immunostaining techniques to quantify the synaptic contacts between hair cells and cochlear nerve terminals with a light microscope (Khimich et al. 2005), where sampling of large numbers of cases becomes feasible. Using one antibody against a major protein in the presynaptic ribbon, located on the hair cell side of each synapse, and a second antibody against a subtype of glutamate receptor, located in a discrete patch at the tip of the cochlear nerve terminal, the synapses in normal ears and in ears exposed to traumatic noise were counted (Kujawa and Liberman 2009).

Armed with this rapid method for quantifying synapses in fixed tissue, it has been shown in both mice and guinea pigs that after a noise exposure that causes only a temporary threshold shift, there is a loss of roughly 50% of the synapses on all the hair cells throughout the cochlear regions showing temporary threshold shift (Kujawa and Liberman 2009; Lin et al. 2011). This dramatic synaptopathy occurs despite no loss of hair cells. The synaptic loss does not recover, i.e., the nerve terminals do not regenerate. Indeed, if the postexposure survival time is extended for months to years, the spiral ganglion cells slowly degenerate despite no loss of hair cells (Kujawa and Liberman 2009). It is the extreme slowness of the spiral ganglion cell loss that allowed this phenomenon to remain undetected for so long.

4 Noise-Induced Neuropathy and Hidden Hearing Loss

Although the spiral ganglion cell degeneration is extremely slow, the synaptic loss is seen immediately postexposure (Kujawa and Liberman 2009), and once the synapse has degenerated, the affected neuron is functionally disconnected from the hair cell and thus carries no auditory information to the central nervous system.

How is it possible for a noise exposure to permanently disconnect 50% of the fibers in the cochlear nerve and yet cause no permanent elevation of cochlear thresholds? OAE thresholds can recover because only the hair cells are required to produce a normal OAE and the hair cells are only transiently damaged and fully recover. The ABR thresholds can recover because the neurons that degenerate are from the subset of cochlear neurons that normally have high thresholds (Furman et al. 2013). The low-threshold fibers survive and mediate the electrical responses to threshold-level stimuli. As the sound pressure of the ABR test increases, the ABR amplitude fails to grow at a normal rate because the high-threshold fibers are not there to be recruited. Thus, the suprathreshold ABRs, e.g., at 80 dB sound pressure level, are attenuated in amplitude in proportion to the loss of high-threshold neurons (Kujawa and Liberman 2009).

In my own work, I have not measured behavioral thresholds in noise-exposed animals, but there is good reason to believe that their “audiograms” would also be normal despite the loss of numerous neural connections. More than 50 years ago, investigators showed that the behavioral audiogram is extremely insensitive to primary neural degeneration. For example, one experiment showed that cochlear nerve lesions in cats resulting in 50–75% loss of cochlear ganglion cells caused no detectable elevation in behavioral thresholds as long as the hair cells were not damaged (Schuknecht and Woellner 1955). A more recent experiment using chinchillas showed that up to 90% of the cochlear nerve fibers could be silenced throughout the entire cochlear spiral without any significant elevation in behavioral thresholds (Lobarinas et al. 2013) as long as the function of the outer hair cell-based cochlear amplifier was unperturbed.

If thresholds are normal, then what is the functional significance of the noise-induced neural loss we have discovered? Our hypothesis is that the importance of the multiplicity of neurons contacting each hair becomes apparent when the listening task becomes more difficult than that presented by the audiogram, which requires only detecting the presence of a tone in a quiet environment. One obvious, and important, example of a more complex task is the understanding of speech in the presence of background noise. It is an audiological truism that people with normal audiograms vary widely in their ability to perform speech discrimination tasks reliably in the presence of background noise and that this performance deficit is an especially salient aspect of age-related hearing loss (see, e.g., Frisina and Frisina 1997).

In summary, it is believed that the audiogram provides a good measure of the condition of the hair cells and that hair cell damage is certainly an important aspect of noise-induced hearing loss. However, recent work shows that the most vulnerable elements are the cochlear nerve fibers. Although the effects of nerve fiber loss are impossible to quantify based on an audiogram, a number of laboratories are pursuing the idea that hearing in noise or performance on other complex auditory tasks may be a useful measure of noise-induced neuropathy.

The most sobering aspect of the work on noise-induced neuropathy is its implications for damage risk criteria. All damage risk criteria are constructed assuming that the audiogram is the gold standard functional test and therefore that an exposure that causes only a temporary threshold shift is essentially benign (National Institute for Occupational Safety and Health 1998). Because this assumption is clearly not true, at least in mice and guinea pigs, it is highly likely that noise exposure is much more dangerous than we thought.

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Chapter 2
Modeled and Measured Underwater Sound Isopleths and Implications for Marine Mammal Mitigation in Alaska

Lisanne A.M. Aerts and Bill Streever

Abstract Before operating air guns in Alaska, industry is usually required to model underwater sound isopleths, some of which have implications for the mitigation and monitoring of potential marine mammal impacts. Field measurements are often required to confirm or revise model predictions. We compared modeled and measured air gun sound isopleths from 2006 to 2012 and found poor agreement. Natural variability in the marine environment, application of precautionary correction factors, and data interpretation in the generation of circular isopleths all contributed to the observed poor agreement. A broader understanding of the realities of modeled and measured underwater sound isopleths will contribute to improved mitigation practices.

Keywords Air gun • Seismic • "Take" estimate • Marine Mammal Protection Act

1 Introduction

In seismic operations, the oil and gas industry tows air guns behind vessels to generate sound impulses. These vessels are generally referred to as "source vessels." Images of the stratigraphy underlying the seabed are generated from reflected sound impulses. These images are used to guide exploration and production drilling, manage existing reservoirs, and identify hazards buried in the seabed. As such, seismic operations are essential to the offshore oil and gas industry.

The sound impulses generated by air guns could, under certain circumstances, "take" marine mammals. The United States Marine Mammal Protection Act (MMPA) requires efforts to prevent "take," a term that means actual injury as well as

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disruption of behavioral patterns (including migration, breathing, nursing, breeding, feeding, or sheltering). In addition, the MMPA requires efforts to document the number of takes that can occur despite preventative measures. Actual observations of impacts meeting the definition of take are rare, in part due to the difficulties associated with making and interpreting observations at sea. With that in mind, sound exposures are often used as a surrogate for takes.

During air gun operations in the Alaskan Arctic, marine mammal mitigation and monitoring required by the government in its administration of the MMPA requires knowledge of the extent of the 190, 180, 160, and 120 dB re 1 μPa root-mean-square (rms) isopleths. Air guns cannot be operated if seals are present within the 190 dB re 1 μPa rms isopleth or if cetaceans are present within the 180 dB re 1 μPa rms isopleth. The 160 and 120 dB re 1 μPa rms isopleths can trigger additional mitigation requirements. Also, animals exposed to impulsive sounds of 160 dB re 1 μPa rms or more (such as those associated with air guns) or continuous sounds of 120 dB re 1 μPa rms or more (such as those associated with vessel operations) are assumed to be potentially taken regardless of whether harm or meaningful behavioral responses are observed.

Take estimates for air gun sounds are generally derived by multiplying the extent of the modeled or measured sound isopleths of 160 dB re 1 μPa rms with the expected species densities from scientific surveys or field observations made during previous seismic operations in the area of interest. Both sound isopleths and species densities are associated with high levels of uncertainty. In this paper, we focus on the uncertainties associated with sound isopleths.

Information on the extent of sound isopleths comes from acoustic models and from acoustic measurements. Acoustic models combine information about source levels with information about factors known to affect sound propagation (including water depth, water temperature, salinity, and seabed characteristics) to yield three-dimensional (distance and depth) estimated distances at which various sound levels are received. Acoustic measurements typically rely on hydrophones recording at numerous distances from a source. Both endfire and broadside measurements are sometimes reported. Endfire measurements, or measurements from the bow and stern aspects of a source vessel, are usually collected using several bottom-founded hydrophones that record air gun sounds while the source vessel approaches and moves away. Broadside measurements from the port or starboard aspects of a source vessel are usually collected by three or more recording hydrophones placed in a line perpendicular to the source vessel's direction of travel. In contrast to acoustic models, acoustic measurements typically yield two-dimensional (distance but not depth) estimated distances at which various sound levels are received. In both cases, to facilitate mitigation and monitoring requirements in the field, isopleths are generally plotted as circles even if models or measurements indicate that actual isopleths have an irregular shape.

Over the past 6 years in the Alaskan Arctic, air gun operators have used both acoustic models (to predict the extent of sound isopleths) and acoustic measurements (to verify the modeled predictions). In this paper, we compare sound isopleths derived from models to those derived from measurements. In addition, we discuss the causes and ramifications of the differences in estimates derived from models and measurements, and we assess the degree to which agreement has improved over time.

2 Data Compilation of Modeled and Measured Sound Isopleths

Modeled sound isopleths from air gun operations in the Alaskan Arctic are generally reported in requests for an Incidental Harassment Authorization (IHA) of marine mammals submitted to the National Marine Fisheries Service (NMFS), the government agency responsible for administering the MMPA as it applies to seals and whales. Detailed results of acoustic measurements conducted during air gun operations of the oil and gas industry are documented in monitoring reports that, according to the IHA stipulations, have to be submitted to the NMFS within 90 days of survey completion.

We obtained IHA requests and 90-day monitoring reports of seismic surveys in the Alaskan Arctic during the period 2006–2012 from the Web site of the NMFS Office of Protected Resources (http://www.nmfs.noaa.gov/pr/permits/incidental.htm; Ireland et al. 2007; Aerts et al. 2008; Funk et al. 2008; Hauser et al. 2008; Hannay and Warner 2009; O'Neill et al. 2010; Chorney et al. 2011; Warner and Hipsey 2011; Warner and McCrodan 2011; McPherson and Warner 2012). We only compiled isopleth information for sound pressure levels that are assumed to have the potential to harm marine mammals (190 and 180 dB re 1 μPa rms for pinnipeds and cetaceans, respectively), that are used for calculating behavioral takes of air gun sounds (160 dB re 1 μPa rms), or that might trigger mitigation requirements under some circumstances (120 dB re 1 μPa rms). When available, we included both endfire and broadside measurements of the air gun sounds.

Modeled and measured isopleths from various air gun operations involving different air gun discharge volumes and taking place in different areas were compiled in a single database. We included the following information if available: year of survey, total air gun discharge volume (in in.^{3}), smallest air gun in array (in in.^{3}), water depth in survey area (in m), modeled distances to the four received sound pressure levels (in m), and measured distances to the four sound pressure levels for both endfire and broadside aspects.

3 Results of Sound Isopleth Comparisons

We compiled 133 records of modeled and measured sound isopleth data from air gun operations in the Chukchi and Beaufort Seas from 2006 through 2012. Air gun operations included offshore marine streamer seismic surveys, ocean bottom cable (OBC) seismic surveys, and shallow hazard surveys. Offshore marine streamer seismic surveys used air gun discharge volumes ranging from 3,000 to 3,390 in.^{3} (up to 24 air guns) and occurred in water depths of 15–50 m. OBC seismic surveys took place in shallower water (1–20 m) and used air gun discharge volumes ranging from 320 to 880 in.^{3} (with up to 16 guns). The shallow hazard surveys for which we compiled sound isopleth data were done in water depths of 15–50 m using 1–4 air guns of 10 in.^{3} each. Modeling and measurements were also done for the mitigation gun,

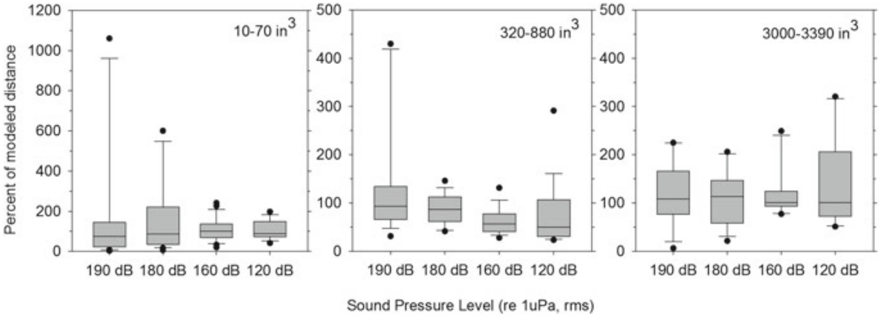


Fig. 2.1 Differences expressed as percentage of modeled distances between measured and modeled sound isopleths for four different sound pressure levels and three air gun volume categories. Boxplots show the 5, 25, 50, 75, and 95% values. Note the different scale used for the 10–70 in.^{3} air gun graph, in which two outliers (1,600 and 3,600% for the 190 and 180 dB re 1 μPa sound levels, respectively) are not displayed. *rms* root-mean-square

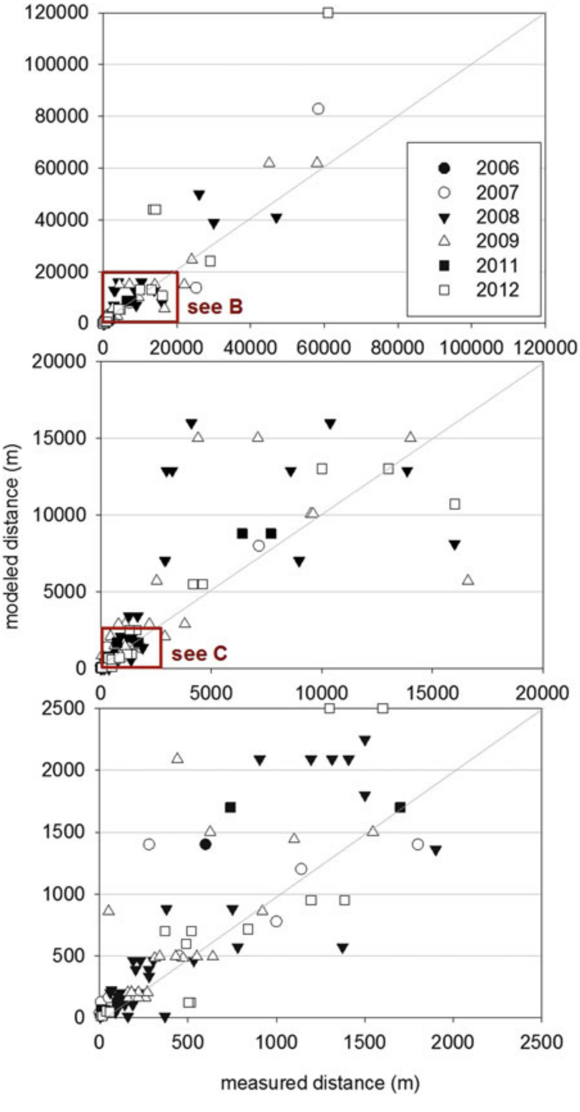
i.e., the smallest gun in the array. Discharge volumes of mitigation guns ranged from 10 to 70 in.^{3}.

Although modeling and measurement occasionally yielded sound isopleths that were in close agreement with one another, differences could be substantial (Fig. 2.1). For example, differences in distances to modeled and measured sound isopleths were as high as 920, 2,900, 13,405, and 130,000 m for the 190, 180, 160, and 120 dB re 1 μPa rms isopleths, respectively. Even for the smallest sources, those with air gun volumes of 10–70 in.^{3}, differences between modeled and measured sound isopleths were as high as 150, 360, 1,120, and 11,392 m for the 190, 180, 160, and 120 dB re 1 μPa rms isopleths, respectively. Percentage differences in measured and modeled sound isopleths from the smaller air gun arrays and higher sound pressure levels were more substantial than for the larger arrays and lower sound pressure levels (Fig. 2.1). In many cases, differences between modeled and measured estimates for a single source along a single transect were positive for some isopleths and negative for others. There was no apparent pattern between modeled and measured distances that would suggest a clear path to a correction factor. Also, there was no evidence of improved agreement over time, as might be expected if methods were improving as experience accumulated (Fig. 2.2). In fact, the only clear pattern was one of generally increasing differences with distance from the source, as would be expected at the larger distance scales associated with isopleths for lower sound pressure levels (Fig. 2.2).

4 Discussion

Distance discrepancies between modeled and measured sound pressure level isopleths can be attributed to a number of causes ranging from inadequate input data for models to decisions about how to interpret modeled and measured data and how

Fig. 2.2 Modeled versus measured distances from several air gun sources to various received sound pressure levels for surveys conducted in the Alaskan Arctic from 2006 to 2012. Points on the *diagonal line* represent 100% agreement between modeled and measured distances. Graphs are shown in three different scales as represented by the *red squares*



to convert output to circular mitigation and monitoring zones. Model predictions of underwater sound isopleths require knowledge of the source and of sound propagation. Underwater sound propagation is complex and dependent on numerous factors, such as, but not limited to, water depth, bottom type and relief, surface reflection, absorption and sound speed profile (influenced by temperature and salinity among other factors), source depth, and source characteristics (e.g., frequency composition, directivity). Many of these factors are subject to temporal and spatial variability and it is unlikely that the data used in models routinely reflect actual conditions during measurements.

Because uncertainty is inherent to modeling, cautionary adjustments are sometimes made to input data. For example, source levels are sometimes elevated by 3 dB re 1 μPa rms. Likewise, conservative interpretations are introduced in the measured sound isopleths that are used for mitigation purposes. In most cases, regression lines drawn through measured data points are adjusted upward to assure that 90% or in some cases 100% of data points are below the regression line used to define mitigation isopleths.

Modeling typically results in isopleths with an irregular shape, reflecting differences to modeled sound pressure levels at different depths and at different directions that are related to source directivity and sound propagation. However, the practical needs of mitigation and monitoring require conversion of these irregular shapes to circles. Typically, these circles are drawn to capture the greatest modeled distance to each isopleth regardless of depth or bearing from the source. Measurements, on the other hand, are typically undertaken along one or a few bearings (forward, aft, and abeam of the source vessel) and at a single depth, typically close to the seabed. Measurements taken abeam of the source vessel are usually based on a small number of data points. Measurements are sometimes extrapolated to capture isopleths beyond the range of the measurements, which has the capacity to introduce substantial errors, especially at 160 and 120 dB re 1 μPa rms. When measurements are collected at more than one bearing, the bearing with the longest distance to each isopleth is often used to define the circle used for mitigation and monitoring. The conversion of irregularly shaped polygons to circles may account for most of the modeling versus measured discrepancies described in this paper.

The challenges associated with modeling isopleths, the practice of limiting measurements to a single depth and a small number of bearings from a source vessel, and the practical need to convert irregularly shaped isopleths to circles for the purpose of mitigation and monitoring explain the poor agreement between modeled and measured isopleths. There is little reason to believe that agreement between modeled and measured isopleths will improve unless substantial changes are made to methods, including standardization of all aspects of the process. However, the real issue may not be one of improving agreement of modeled and measured isopleths but rather one of applying mitigation distance requirements that adequately protect marine mammals without unnecessarily disrupting seismic operations. This requires not only improved methods of defining sound isopleths but also an improved understanding of the levels and kinds of sounds likely to harm marine mammals and improved methods of detecting and ranging marine mammals under field conditions.

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Chapter 3

Peer-Reviewed Studies on the Effects of Anthropogenic Noise on Marine Invertebrates: From Scallop Larvae to Giant Squid

Natacha Aguilar de Soto

Abstract Marine invertebrates at the base of oceanic trophic webs play important ecological and economical roles supporting worldwide fisheries worth millions. There is an increasing concern about the effects of anthropogenic noise on marine fauna but little is known about its effects on invertebrates. Here the current peer-reviewed literature on this subject is reviewed, dealing with different ontogenetic stages and taxa. These studies show that the noise effects on marine invertebrates range from apparently null to behavioral/physiological responses to mortalities. They emphasize the need to consider potential interactions of human activities using intense sound sources with the conservation and fisheries of local invertebrate stocks.

Keywords Underwater noise • Seismic exploration • Shipping • Larval development

1 Introduction

Despite the global economic and ecological importance of invertebrates (Anderson et al. 2011), there are very few peer-reviewed papers investigating how they may be impacted by anthropogenic noise (Morley et al. 2014). This is in contrast to a growing literature about the effects of noise on fish (e.g., Popper and Hastings 2009). Most studies on the effects of noise on marine invertebrates are

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reported as industry or government reports, and these are commonly cited in the absence of appropriate peer-reviewed references. It is important to submit these reports to the peer-review process to make them generally available in the common scientific literature. They deal most often with the effects of seismic sounds on invertebrates, which have been studied more than the effects of other intense noise sources such as shipping, pile driving, or underwater explosions. The scarcity of peer-reviewed literature reporting experimental studies about the effects of underwater anthropogenic noise contrast with the widespread social concern about the effects of seismic and other human noise sources on fisheries. Despite uncertainties about how underwater noise may affect marine fauna, several countries have already implemented regulations that reduce the overlap between seismic surveys and fishing activities. These regulations increase the cost of exploration and so have important economic consequences. However, the absence of regulations could also be costly if the claimed harm is occurring.

Assessing the potential for sound to impact invertebrate fauna is complicated by the widely different responses at the behavioral and physiological levels that are expected from different species belonging to the large number of phyla of marine invertebrates. Moreover, ontogenetic stages from egg to larvae and adult forms may be impacted in different ways. Thus, a conservative approach must be applied when generalizing the results about the effects or apparent lack of noise impacts recorded in studies on a given taxa or ontogenetic stage, using a particular method. Some of the basic concepts that should be considered when investigating and reporting the effects of noise and when applying these results to design mitigation measures for anthropogenic noise sources are discussed here.

(1) Animals may not be able to escape. It is often expected that animals will avoid disturbing noise sources. However, many species are territorial or become territorial at certain times of the year, e.g., when guarding nests, whereas other species have limited movement capabilities. Both cases apply to many invertebrate taxa. Animals may interpret sound as a predator stimulus and respond to it with immobility. This is a typical response to predation threat (Brown and Smith 1998), probably to avoid indicating their presence with hydrodynamic cues. Also, animals may have restricted movements if they are dazed or disoriented by the sound exposure. For example, Solé et al. (2012) reported that cephalopods showed a light startle response before remaining motionless at the bottom of the tank during the rest of the exposition and after it (none ate any more mated, or laid eggs) until they were killed up to 96 h later; Fewtrell and McCauley (2012) also reported changes in swimming behavior and immobility in squids exposed to seismic sounds.

(2) The conclusions must be scientifically correct and fit the power of the experimental protocol. Studies target discrete questions and their conclusions should not be overinterpreted. For example, evaluations of fishing catch rates before and after noise exposure may show stable or even increased captures. This is a valid result for the fishery, but it does not provide any conclusions about the impact on the individuals or the stock. Behavioral responses of sound-exposed

animals, such as immobility, may be neutral to or favor capture by fishing methods such as trawling. However, acoustic damage to the individuals cannot be ruled out unless this is properly tested. Another example of the importance of restricting conclusions to the concrete analysis performed is that tissue/cellular damage is not homogeneous. Thus, analysis of the impact in some tissues may reveal no damage, whereas serious injury may have occurred in other body areas. André et al. (2011) and Solé et al. (2012) reported that no pathologies were found in any tissues of cephalopods exposed to noise except in their statocyst system, which were reported as incompatible with survival.

(3) Survival in the laboratory is not comparable to survival in the wild. Monitoring of animal survival in the laboratory implies controlled experimental conditions where animals are fed and protected from predators. This is an important source of bias because controlled conditions provide a sheltered environment where animals suffering recoverable behavioral or physiological damages may survive. In a natural environment, debilitated individuals are subject to higher predation risk and may have reduced foraging success, limiting their survival in the wild.

2 Summary of Peer-Reviewed Papers on the Effects of Noise on Invertebrates

Findings of the papers dealing with the effects of anthropogenic noise in different phyla of invertebrates that have been published in peer-reviewed journals are summarized here. A schematic view is provided in Table 3.1.

2.1 Aguilar de Soto et al. (2014) Scientific Reports

This paper provides the first evidence that noise exposure during development can produce body malformations in larvae of marine invertebrates. New Zealand scallop larvae exposed to playbacks of seismic pulses in the laboratory showed significant developmental delays and 46% developed body abnormalities. Similar effects were observed in all independent samples exposed to noise, whereas no malformations were found in the control groups (4,881 larvae were examined). Malformations appeared in the D-veliger larval phase, perhaps due to the cumulative exposure attained by this stage or to a greater vulnerability of the D-veliger phase to sound-mediated physiological or mechanical stress. Such strong impacts suggest that abnormalities and growth delays may also result from lower sound levels or discrete exposures during the D-stage, increasing the potential for routinely occurring anthropogenic noise sources to affect the recruitment of wild scallop larvae in natural stocks. The exposure consisted of the playback in a large tank of a seismic pulse

Table 3.1 Results of peer-reviewed literature on noise-impact studies in invertebrates

Reference	Species	Summary results	Total duration	Levels	Frequency	Noise exposure
Aguilar de Soto et al. (2013)	Scallop larvae	Significant delay in development and 46% of larvae with malformations	90 h of pulses every 3 s	SEL pulse 163 dB rms re 1 μPa^2·s at 3–4 ms^{-2}	−3 dB band at 89–129 Hz	Tank playback of prerecorded seismic array
André et al. (2011). See Solé et al. (2012) for details and additional results						
Andriguetto-Filho et al. (2005)	Three species of shrimps	No decrease in trawling catch rates nor shrimp density	1 day of air gun pulses, each 12 s	Peak source level of 196 dB re 1 μPa at 1 m	Not measured	Field Four air gun seismic array
Branscomb and Rittschof (1984)	Barnacle larvae	Lower settlement in cyprid larvae up to 13 days old	20 h or more	Not reported	30 Hz 20–40 Hz	Laboratory Hull Tender
Fewtrell and McCauley (2012)	Squid	Startle responses and behavioral changes increasing with sound level	Air gun passes ≤1 h long Pulse rate 10 s	136 to >162 dB re 1 μPa^2·s	−10 dB band at ≈ 20–70 Hz	Field One seismic air gun
Guerra et al. (2011)	Giant squid	Two atypical mass strandings. Damages to tissues and statocysts	Seismic survey	Ten air gun seismic array	Seismic pulses	Field Air gun array
Kight and Swaddle (2011)	Varied	Excellent review of mechanistic effects of noise at physiological and cellular level	Varied	Varied	Varied	Many

Lagardère (1982)	Shrimp	Reduced growth, feeding and reproductive rates Increased metabolic rate (O_2 intake and ammonia excretion) Reduced growth and weight gain	Compared usual ambient in rearing tanks against soundproof conditions 30 dB lower. Responses started after a few hours and did not decrease in 5 days of experiment			Tank playback
Lagardère and Régnault (1980)						
Regnault and Lagardère (1983)						
Parry and Gason (2006)	Rock lobster	No decrease of fishing captures observed	Several seismic surveys in Western Australia (statistical analysis of catch rate in fishing records)			Field Seismic arrays
Pearson et al. (1994)	Crab larvae	Tank following after field exposure showed no increase in mortality nor time to molt between larvae exposed to 1 seismic pulse and the control group	One seismic pulse	231 dB re 1 µPa	–	Field/tank Seismic array of seven air guns
			All larvae (including control) exposed to elevated ambient noise in the field of 156–168 dB re 1 µPa			
Solé et al. (2012)	Cuttlefish, squid	Strong damages to statocyst system	2 h 1-s sweep period	Median/peak RL: 157/175 dB re 1 µPa	50–400-Hz sweep	Tank low-frequency sweeps
Wale et al. (2013a)	Shore crabs	Size-dependent increase in oxygen consumption	Single/repeated playback of 7 min	148–155 dB re 1 µPa rms	–10 dB bandwidth <2.4 kHz or <300 Hz	Tank playback Ship noise
Wale et al. (2013b)	Shore crabs	Effects on feeding behavior. Unrighted noise-exposed crabs turned over faster and retreated to shelter slower.				

SEL sound exposure level, *rms* root-mean-square recorded at tens of kilometers from a seismic survey vessel (details in Table 3.1). The noise-exposed and control groups were several independent flasks with eggs from the same egg mix. The flasks were located in a tank with a J9 transducer emitting the playback while the control flasks were located at the same time in an adjacent tank with same conditions except for the playback.

2.2 André et al. (2011) Frontiers in Ecology and the Environment and Solé et al. (2012) Deep-Sea Research Part II-Topical Studies in Oceanography

These papers present results showing the first morphological and ultrastructural evidence of massive acoustic trauma in four cephalopod species (*Sepia officinalis*, *Octopus vulgaris*, *Loligo vulgaris*, and *Illex condietii*) subjected to low-frequency playbacks of a 50–400-Hz 1-s sweep for 2 h from an air speaker. The authors reported a received level of 157 dB re 1 µPa in the tank holding the animals, with peak levels up to 175 dB re 1 µPa. Exposure to low-frequency sounds resulted in permanent and substantial alterations of the sensory hair cells of the statocysts, the structures responsible for the animals' sense of balance and position. The analysis was performed using scanning (SEM) and transmission (TEM) electron microscope techniques of the whole inner structure of the cephalopods' statocyst, especially on the macula and crista. All exposed individuals presented the same lesions and the same incremental effects over time, which were absent in control individuals that had been exposed to the same treatments except for the noise playback.

Lesions were evident in animals killed from 0 to 96 h after exposure, with no clear evidence of recovery, although the authors observed scarring processes in some specimens at 48 h. In contrast, the most important lesions on the macula and crista epithelia were observed on the specimens killed 96 h after exposure. The authors discussed that this degenerative process may be due to the cytotoxic effect of glutamate, which usually works as a neurotransmitter but can be released in excess as a response to stressful loud noise, leading to neuronal and sensorial epithelium damage.

2.3 Andriguetto-Filho et al. (2005) Continental Shelf Research

The authors reported on the first study to explicitly assess the impact of seismic prospecting on shrimp resources. They measured bottom trawl yields of a nonselective commercial shrimp fishery comprising the Southern white shrimp *Litopenaeus schmitti*, the Southern brown shrimp *Farfantepenaeus subtilis*, and the Atlantic seabob *Xyphopenaeus kroyeri* (Decapoda, Penaeidae) before and after the use of an array of four synchronized air guns (Table 3.1). Their results did not detect significant decreases in the catch rates of the trawls nor in the density of the species in the area within a day after the seismic exposure was finished.

2.4 Branscomb and Rittschof (1984) Journal of Experimental Marine Biology and Ecology

Inhibition of barnacle settlement was achieved using low-frequency (30-Hz) sound waves on laboratory-reared larvae of *Balanus amphitrite*. Less than 1% of very young cyprid larvae (0 days old) settled in the presence of the sound waves. Cyprids caught in plankton tows responded very similar to laboratory-reared larvae. Although the percentage of settlement tends to increase with older larvae, low-frequency sound reduced the percentage of metamorphosis for cyprids up to 13 days old. The exposure was performed with an nondescribed commercially available device, the Hydro-Sonic Hull Tender (Scientific Technologies, Aiken, SC).

2.5 Fewtrell and McCauley (2012) Marine Pollution Bulletin

In this experiment, squid in large cages in the field were exposed to passes in the 5–800-m range of a single air gun (source level at 1 m of 192 dB re 1 $\mu Pa^2 \cdot s$) shooting every 10 s. Squid showed startling responses and behavioral responses from the minimum received levels (RLs) and increased with the increasing RL. RLs ranged from 136 to >162 dB re 1 $\mu Pa^2 \cdot s$. Behavioral changes included changes in swimming behavior and vertical location in the cage and reduced movement.

2.6 Guerra et al. (2011) Biological Conservation

These authors associated two geophysical seismic surveys to two atypical mass strandings of giant squid (*Architeuthis dux*), with some squid showing extensive tissue damage. Long-term records of strandings of giant squid in the area (Asturias, northern coast of Spain) do not exceed one or two animals per year except in autumn 2001 and September 2003. In these two cases, five and four animals, respectively, were found stranding or floating for short time periods and in localized areas. These cases resulted in a significant increase in the probability of giant squid strandings in the area. The specimens in the mass strandings ranged from 60 to 200 kg in weight and 7–12 m in total length. They showed no obvious external cause of death, but internal examinations showed that two of the squid suffered extensive damage to internal muscle fibers; their stomachs were ripped open and their digestive tracts were mangled. The squid also suffered severe damage to their statocysts, the structures responsible for the animals' sense of balance and position. The authors proposed that this disorientation may be the cause of death of the squid without clear organic damage if these moderately active, buoyant giant squid floated toward the surface where they died. Moving from deep cold waters to warmer and shallower waters causes oxygen desaturation given the low affinity to oxygen at a high temperature of their oxygen carrier protein hemocyanin.

2.7 Lagardère (1982) Marine Biology and Regnault and Lagardère (1983) Marine Ecology Progress Series

The team of Regnault and Lagardére produced several papers reporting that a continuous raised ambient noise in aquariums of ~30 dB at 25–400 Hz increased metabolism (higher oxygen consumption and ammonia excretion) and reduced growth and reproductive rates in brown shrimp (*Crangon crangon*). The increases in metabolic rate were expressed within a few hours, and there was no evidence of habituation during the experiment (5 days). The authors interpreted the observed increases in cannibalism and mortality rates and decreased food uptake to be signs of stress.

2.8 Parry and Gason (2006) Fisheries Research

The effect of seismic discharges on rock lobsters was investigated through statistical analysis of the coincidence between seismic surveys and changes in commercial catch rates in western Victoria between 1978 and 2004. In 12 depth-stratified regions, the number of acoustic pulses during seismic surveys was correlated with the catch per unit effort (CPUE) of rock lobsters to determine whether catch rates were affected in the years after seismic surveys. In three regions subjected to intensive seismic surveys, two-way analysis of variance was used to detect short-term (weekly) changes in the CPUE before, during, and after these seismic surveys. There was no evidence that the catch rates of rock lobsters were affected by seismic surveys in the weeks or years after the surveys. The authors discussed these results in the context of most seismic surveys occurring in deep water where impacts would be expected to be minimal.

2.9 Pearson et al. (1994) Marine Environmental Research

Larvae reared in the laboratory were transported to the field where they were exposed to one pulse from a seven air gun array or to a mock exposure without the array actually shooting (control group). Ambient-sound levels measured during the control periods of the experiment were abnormally high due to the compressor of the air gun array and varied from 156 to 168 dB re 1 μPa. Larvae were then transported back to the laboratory for monitoring in controlled conditions. Larvae exposed to the seismic pulse did not show differences in the survival rate and the time to molt compared with the control group.

2.10 Wale et al. (2013a) Biology Letters and Wale et al. (2013b) Animal Behaviour

The authors used controlled experiments to investigate in the laboratory how the physiology and behavior of the shore crab (*Carcinus maenas*) is affected by both single and repeated exposure to ship-noise playback. Crabs experiencing ship-noise playback consumed more oxygen, indicating a higher metabolic rate and potentially greater stress, than those exposed to ambient-noise playback. The response to single-ship noise playback was size dependent, with the heavier crabs showing a stronger response than lighter individuals. Also, the authors observed subtle changes in the feeding behavior of the crabs and differences in the time to retreat to shelter and time to turn to recover a right position, suggesting that noise-exposure may affect predator responses in the wild.

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Chapter 4
Sources of Underwater Sound and Their Characterization

Michael A. Ainslie and Christ A.F. de Jong

Abstract Because of the history of sonar and sonar engineering, the concept of "source level" is widely used to characterize anthropogenic sound sources, but is it useful for sources other than sonar transmitters? The concept and applicability of source level are reviewed for sonar, air guns, explosions, ships, and pile drivers. International efforts toward the harmonization of the terminology for underwater sound and measurement procedures for underwater sound sources are summarized, with particular attention to the initiatives of the International Organization for Standardization.

Keywords Source level • Environmental cost • Standardization

1 Introduction

The first intensive research into underwater sound took place 100 years ago. In 1914, the Canadian inventor Reginald Fessenden was the first to successfully detect an iceberg (see Fig. 4.1) two years after the loss of the RMS Titanic. Echolocation systems capable of detecting and localizing U-boats were developed during World War I by physicists Langevin in France and Boyle in the United Kingdom (Ainslie 2010). The need to understand the performance of these early underwater detection systems, known today as sonar, led to the development of a mathematical framework known as the "sonar equations" (Urick 1983), within which sound sources are characterized by their "source level" (SL). Knowledge of the sonar SL, combined with "propagation loss" (PL) and other related terms, enables calculation of the expected detection range (Horton 1959; Urick 1983; Ainslie 2010).

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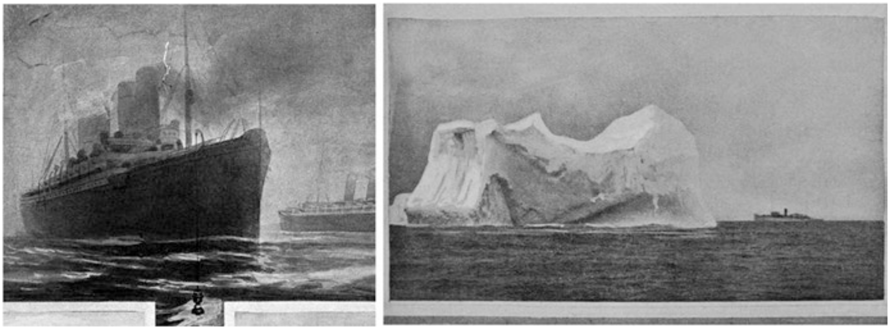

Fig. 4.1 Using Fessenden's oscillator, on 27 April 1914, the United States Revenue Cutter Miami detected an iceberg at a distance of "two and one-half miles." Reproduced with permission from the National Oceanic and Atmospheric Administration, Department of Commerce, Washington, DC

A proper assessment of environmental effects requires a proper understanding of the sound field in the context of the sources that produce it (the "soundscape"). Characterization of underwater sound sources is the subject of this paper. Section 2 contains a traditional description in terms of SL, followed by alternative descriptions in Section 3. Progress toward standardization is described in Section 4.

2 Traditional Characterization of Underwater Sound Sources

Underwater sound sources are often characterized in terms of a quantity known as "SL." This characterization results from the relevance of SL to the understanding and quantification of the performance of underwater detection, classification, and localization systems such as sonar, echo sounders, and air gun arrays. In the twentieth century, sonar (this term is used to mean any system that uses underwater sound to obtain information about the sea, its contents, and its boundaries) was the main reason for mankind's interest in underwater sound (Horton 1959; Hersey 1977). Today, interest is growing in underwater sound as a possible environmental pollutant, in which case it is often referred to as "noise." Does it make sense to use the concept of SL for this new application? Perhaps, but this depends partly on the type of source and partly on how this concept is used in relation to the specific environmental concern. Here, we review important sources of underwater sound, clarifying the important difference in the meaning of SL from case to case. Specific sources considered are sonar, ships, air guns, explosives, and pile drivers. Before considering specific cases, we draw attention to two general misconceptions.

First, SL is a property of a sound source and not of the sound field close to the source. It is closely related to the sound power radiated by the source, and for an omnidirectional source of power W in an infinite uniform lossless medium of impedance ρ,c is given by (Ainslie 2010)

$$\mathrm{SL} = 10\log_{10}\frac{W\rho c/(4\pi)}{p_{\mathrm{ref}}^2 r_{\mathrm{ref}}^2} \tag{4.1}$$

where $p_{\mathrm{ref}} = 1$ μPa and $r_{\mathrm{ref}} = 1$ m are standard reference values of pressure and distance, respectively. The term is defined by national (American National Standards Institute [ANSI]/Acoustical Society of America [ASA] 1994) and international (IEC 1994) standards bodies as the sound pressure level (SPL) at the standard reference distance from the source; unfortunately, the applicability of the ANSI/ASA (1994) and IEC (1994) definitions is limited to a point source at low frequency (no absorption). A more appropriate definition for a real source would require the SL to be a far-field property of the source (Urick 1983; Ainslie 2010). It is therefore more correct to define SL as the level in decibels of the square of the product of the distance r from a point in the far field to the source and the root-mean-square (rms) sound pressure p_{rms} at that distance, i.e., evaluated in a specified direction

$$\mathrm{SL} = 10\log_{10}\frac{p_{\mathrm{rms}}^2 r^2}{p_{\mathrm{ref}}^2 r_{\mathrm{ref}}^2} \tag{4.2}$$

The far field is the region far from the source in which the pressure field scales inversely with increasing distance and is proportional to the local radial particle velocity (Morfey 2001). The applicability of Eq. (4.2) is limited to the same ideal medium as Eq. (4.1). For example, the source must be sufficiently far from any reflecting boundary that the sound field at r is unaffected by the presence of that boundary. The reference value for SL, which follows from Eq. (4.2), is equal to $p_{\mathrm{ref}}^2 r_{\mathrm{ref}}^2 = 1$ μPa^2 m^2. For example, for a source with far-field rms pressure satisfying the relationship $p_{\mathrm{rms}}^2 r^2 = 10^{18}$ μPa^2 m^2, the natural way to express the numerical value of SL in the conventional format of "decibels re <reference value>" is therefore "SL = 180 dB re 1 μPa^2 m^2." Some authors prefer to take the square root of the reference value so that this becomes "SL = 180 dB re 1 μPa m," whereas others use "SL = 180 dB re 1 μPa @ 1 m." The intended meaning is the same in all three cases. In our opinion, the use of "1 μPa @ 1 m" as a reference value is inappropriate because it reinforces the incorrect impression that the SL is equal to the SPL at a distance of 1 m from the real source.

Second, can a useful meaning necessarily be assigned to the term SL for any given source of underwater sound? Bearing in mind that SL is a property of the sound source, defined in terms of its far-field sound pressure, if that source does not have a far field, the concept loses its traditional meaning and a new definition of the term SL would be needed if used for such a source.

2.1 Sonar

The concept of SL is well suited to an active sonar transmitter. In its simplest form, the sonar equation relates the monopole source level (MSL; to distinguish it from the dipole source level [DSL]) to the SPL and PL via SPL = MSL − PL.

2.2 Ships

A useful model for understanding the sound radiated by a surface ship is a monopole (i.e., a point omnidirectional source) close to the sea surface combined with its surface image. The SL of the resulting dipole is given by the right side of Eq. (4.2), where p_{rms} is the rms pressure in the far field of the dipole. Given the far-field radiation pattern of a dipole comprising a monopole pulsating at frequency f at depth d and its image (in antiphase) at depth $-d$, it follows that the DSL is given by $\mathrm{DSL} = \mathrm{MSL} + 10\log_{10}\{4\sin^2[(2\pi fd/c)\sin\theta]\}$, where the MSL is the MSL on its own and θ is the elevation angle. A related term is "radiated noise level" (RNL), which for a specified direction is defined as $\mathrm{RNL} \equiv \mathrm{SPL} + 10\log_{10}(r^2/r_{\mathrm{ref}}^2)$. This quantity is related to MSL and DSL via the equations $\mathrm{RNL}(r) = \mathrm{MSL} + 10\log_{10}(r^2/r_{\mathrm{ref}}^2) - \mathrm{PL}(r) = \mathrm{DSL} - 10\log_{10}\{4\,(r_{\mathrm{ref}}^2/r^2)\sin^2[(2\pi fd/c)\sin\theta]\} - \mathrm{PL}(r)$. Sometimes RNL is referred to as SL (Arveson and Vendittis 2000) or "affected SL" (ANSI/ASA 2009).

There is an increasing interest in the use of propagation models to compute the sound field associated with individual or multiple ships. The quantity that is needed for such computations is the MSL, as measured, for example, by Wales and Heitmeyer (2002), with an associated monopole depth. A map showing the predicted geographical distribution of sound in the Dutch North Sea is shown in Fig. 4.2.

Because of the broadband nature of a surface ship as a sound source, it is common practice to express its SL in the form of spectral density or in third-octave bands. For example, the monopole source spectral density level (MSSDL) of merchant ships from Wales and Heitmeyer (2002), averaged over their measurements, using the widely used reference bandwidth of 1 Hz, is MSSDL = 176.9 dB re 1 $\mu\mathrm{Pa}^2\,\mathrm{m}^2/\mathrm{Hz}$ at 30 Hz. A monopole depth of $d = 5$ m corresponds to a dipole source spectral density level (evaluated at an elevation angle $\theta = \pi/6 = 30°$) of 172.8 dB re 1 $\mu\mathrm{Pa}^2\,\mathrm{m}^2/\mathrm{Hz}$.

2.3 Air Guns

The proximity of an air gun array to the sea surface makes it useful, as with a surface ship, to think of a dipole formed by a near-surface monopole combined with its surface image (known as a "ghost"). The transient nature of an air gun pulse makes it useful to introduce the concept of a time-domain air gun "signature," defined as the product $r \times p(t)$, where $p(t)$ is the instantaneous sound pressure in the

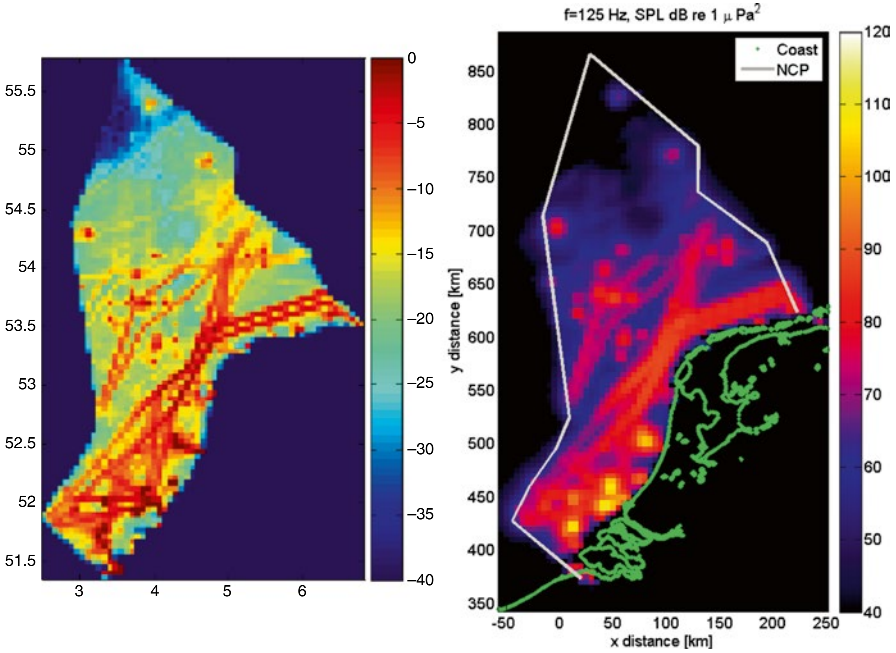

Fig. 4.2 Annually averaged sound pressure level (SPL) due to shipping in the Dutch North Sea, in one-third octave band centered at 125 Hz (*right*), calculated from annually averaged shipping density N [the quantity plotted is $10\log_{10}(25N/\mathrm{km}^{-2})$] (*left*). Reproduced with permission from H. Ö. Sertlek

far field of the source and its image at distance r. The maximum magnitude of the signature $S = r_{\max}|p(t)|$ is sometimes referred to as the "source strength." The level of the square of the source strength is known as the zero-to-peak (dipole) source level $(\mathrm{DSL}_{\mathrm{zp}}) = 10\log_{10}[S^2/(p_{\mathrm{ref}}^2\ r_{\mathrm{ref}}^2)]$. A single gun might have source strength $S = 10^{11}$ μPa m (i.e., 1 bar m), corresponding to a $\mathrm{DSL}_{\mathrm{zp}} = 220$ dB re 1 μPa² m². Similarly, a small air gun array might have $S = 10^{12}$ μPa m (10 bar m), corresponding to a $\mathrm{DSL}_{\mathrm{zp}} = 240$ dB re 1 μPa² m². For a transient, one can calculate the integral (E) with respect to time of the squared source signature $E = \int p(t)^2\, r^2 \mathrm{d}t$, leading to the concept of the (dipole) energy SL (DESL) as given by

$$\mathrm{DESL} = 10\log_{10}\frac{E}{p_{\mathrm{ref}}^2 r_{\mathrm{ref}}^2 t_{\mathrm{ref}}} \tag{4.3}$$

The value $t_{\mathrm{ref}} = 1$ s is widely used for the reference time. The reference value for the DESL is therefore 1 μPa² m² s. The source signature, source strength, $\mathrm{DSL}_{\mathrm{zp}}$, and DESL can be properties either of an individual air gun or of an air gun array.

2.4 Explosives

The acoustical characteristics of explosions in deep water are well understood (Weston 1960). Close to the source, the usual sonar equation is not applicable due to nonlinear propagation effects. For example, there is no "spherical spreading" region in which sound pressure decreases linearly with increasing distance. For this reason, the concepts of source signature or zero-to-peak SL are not useful ones for explosions. At a distance exceeding 5,000 charge radii from the source, the nonlinear effects become minimal, becoming useful to define the (monopole) energy level (MESL) as the right side of Eq. (4.3) in this linear region. An explosive of equivalent TNT charge mass equal to 1 kg radiates ~1 MJ of acoustic energy into the linear region, corresponding to a MESL = 231 dB re 1 $\mu Pa^2\ m^2$ s (Ainslie 2010). The MESL increases by 10 dB for each factor of 10 increase in charge mass, leading, for example, to a MESL = 251 dB re 1 $\mu Pa^2\ m^2$ s for a 100-kg charge.

2.5 Pile Drivers

Offshore construction of wind farms requires the installation of large steel piles into the seabed to support the turbines. Techniques for doing so include impact and vibratory pile driving. Impact pile driving involves striking the pile with a large hammer with energy on the order of 1 MJ, a small fraction of which (typically 1–3%) is radiated as sound (de Jong and Ainslie 2008; Dahl and Reinhall 2013; Zampolli et al. 2013). Models of the sound radiated by impact pile driving have been published using both time-domain (Reinhall and Dahl 2011) and frequency-domain (Zampolli et al. 2013) finite-element methods, techniques that are limited to short ranges (on the order of 100 m from the pile). A pile in shallow water does not have a far field, which means that the conventional definition of SL in terms of the source's far field is not applicable (Ainslie et al. 2012). This makes it uncertain whether long-range propagation models, which traditionally require SL as an input, are suited to calculate the field at distances of interest (~10 km and greater).

3 Alternative Characterizations

Several different kinds of SL were described in Section 2, but is it the right parameter to use for the assessment of the risk of environmental effects? What matters to the animals is the received field, which is affected by the real source, including its directivity and duty cycle, and by properties of the environment such as water depth, absorption, and critical angle. An indication of environmental cost that takes into account the source's footprint in space and time, thereby incorporating all of these effects except water depth and critical angle, is the free-field energy (FFE) introduced by Ainslie et al. (2009) and Ainslie and Dekeling (2011). The FFE is proportional to a source's duty cycle and directivity factor and inversely proportional to the absorption coefficient of the propagation medium. Its use enables ranking of the environmental cost of disparate sources (that might have different frequencies, different beam patterns, and duty cycles) if the comparison is made in the same environment. For example, Ainslie et al. (2009) showed that shipping and seismic surveys were the activities responsible for the largest amount of sound energy in the Dutch North Sea (the combined FFE of both being on the order of 10 MJ, about 10 times more than for pile driving and explosions and at least 500 times more than for sonar). Using a scaling factor of 250 based on the number of ships worldwide (Hildebrand 2009) and arbitrarily assuming that activities associated with seismic surveys scale by the same factor lead to an expected global FFE from these two activities on the order of 2,500 MJ.

4 Toward Standardization

4.1 Standardization of Terminology

Ambiguities in the terminology of the sonar equation are pointed out by Ainslie and Morfey (2005) and Ainslie (2008). Because the same terminology is used for other applications of underwater acoustics, these other branches suffer from the same ambiguity, ultimately limiting our ability to communicate effectively and therefore to make progress. Although some national terminology standards exist, international acceptance requires an international standard. The creation of an ad hoc European working group led to a consensus report (Ainslie 2011), which has been adopted by international expert groups in Europe (Dekeling et al. 2013) and worldwide (Boyd et al. 2013). The Underwater Acoustics Sub-Committee of the International Organization for Standardization (ISO/TC 43/SC 3) has established a working group with the objective of developing an underwater acoustical terminology standard by 2015. That working group just met for the second time in Budapest during Aquatic Noise 2013.

4.2 Standardization of Measurement Procedures

Standardization of terminology is an essential first step that facilitates progress on measurement and reporting standards. Working groups under ISO/TC 43/SC 3 and ISO/TC 8/SC 2 are in an advanced stage of developing standard procedures for measuring the radiated noise of ships. The first result is available as International Organization for Standardization (ISO)/Publicly Available Specification (PAS) 17208–1:2012 (2012). A third working group under ISO/TC 43/SC 3 is developing a standard for the measurement of radiated noise from marine pile driving. The SC 3 work program contains proposed work items for the measurement of ambient sound and of sound from air guns and active sonars.

5 Conclusions

For historical reasons, underwater sound sources are often characterized by their SL, and this term has proved its worth for sonar applications. If the sonar target is in the far field, this enables the efficient prediction of performance for sonar design or evaluation. The same reasoning applies to the environmental impact assessment: If the receiver (whether an animal's ear or a man-made hydrophone) is in the far field of a sound source, knowledge of the SL provides a means to predict the SPL or sound exposure level at the receiver by straightforward application of the sonar equation.

Nevertheless, the absence of an international standardization of terminology has led to confusion. SL is one of the most difficult terms in the sonar equation to comprehend, partly because of the multiple definitions and uses of this term. On its own, because it doesn't take into account parameters such as directivity, duty cycle, or frequency, it is also of limited practical use as an indicator of environmental impact. In this role, the FFE of a source, which does take into account these parameters, is a more useful indicator. Application of the FFE to a case study leads to the conclusion that shipping and seismic surveys are responsible for most of the low-frequency sound energy in the Dutch North Sea. The use of SL is especially problematic in representing the sound radiated by a pile driver in shallow water because of the absence of a far field for such a source.

Lack of standardization, especially of terminology, impedes progress. It prevents us from communicating our ideas unambiguously and limits advancement of underwater acoustics as a science.

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Chapter 5
Assessment of Marine Mammal Impact Zones for Use of Military Sonar in the Baltic Sea

Mathias H. Andersson and Torbjörn Johansson

Abstract Military sonars are known to have caused cetaceans to strand. Navies in shallow seas use different frequencies and sonar pulses, commonly frequencies between 25 and 100 kHz, compared with most studied NATO sonar systems that have been evaluated for their environmental impact. These frequencies match the frequencies of best hearing in the harbor porpoises and seals resident in the Baltic Sea. This study uses published temporary and permanent threshold shifts, measured behavioral response thresholds, technical specifications of a sonar system, and environmental parameters affecting sound propagation common for the Baltic Sea to estimate the impact zones for harbor porpoises and seals.

Keywords Seal • Harbor porpoise • Behavioral effects • Temporary threshold shift • Permanent threshold shift

1 Introduction

In recent years, naval sonars have received a lot of attention because there have been numerous unexpected strandings of various marine mammals shortly after sonar exercises (see an overview in OSPAR 2009). Navies use sonars to search for and classify objects in the water volume, on the surface, on the seabed, and in the seafloor. A sonar system can typically use a range of different frequencies and pulses. Anthropogenic noise in terms of sonar pulses may affect marine life in different ways. Hearing and internal organs can be directly affected, but sound may also induce behavioral effects that, in turn, may affect critical life functions such as reproduction, feeding, and separation between mother and offspring. The most studied systems in terms of environmental effects are the antisubmarine warfare sonar systems used by NATO forces, the low-frequency active sonar (LFAS) and

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midfrequency active sonar (MFAS) that operate between 0.1 and 10 kHz (Hildebrand 2004; Dolman et al. 2009). There are other sonars that are used to detect mines and torpedoes. These function at higher frequencies (100–400 kHz) but are not discussed in this study. However, in shallow seas, the common LFAS and MFAS systems do not work satisfactorily for hydrographic reasons. Therefore, antisubmarine warfare sonars that are designed to operate in the shallow brackish water of the Baltic Sea use other frequencies, typically between 20 and 100 kHz, and pulses than the previously studied systems. There is a lack of scientific results that can be applied to estimate the environmental effects of sonars transmitting at these frequencies. In addition, sonars used in the Baltic Sea transmit pulses at frequencies that match the most sensitive areas in terms of hearing of several resident species of marine mammals.

Compared with other seas, the Baltic Sea has only a few resident marine mammal species that potentially could be disturbed by military sonars and risk hearing damage. These are three earless seal species, *Phoca vitulina* (harbor seal), *Halichoerus grypus* (gray seal), and *Pusa hispida botnica* (ringed seal), and one whale species, *Phocoena phocoena* (harbor porpoise). The distribution of these species overlap to some extent. Of these four, *P. phocoena* has the best hearing and is more sensitive to noise than the seals. To date, no stranded or injured animals have been reported as a result of sonar use in the Baltic Sea.

This study estimates the scale of negative effects on marine mammals by calculating impact zones from active sonar systems commonly used in the Baltic Sea. Here, by impact zone, we mean a zone around the transmitter such that if an animal is within this zone, it risks injuries or behavioral disturbances. The calculations are based on sound propagation characteristics of the Baltic Sea combined with the most recent scientific data on sound level thresholds for physical and behavioral effects.

2 Methods

2.1 Sound Propagation Modeling and Sound Source

Sound propagation depends strongly on the environment. The propagation can be estimated by numerical modeling if the sound velocity profile, i.e., the variation of sound speed with depth, is known. At long ranges, absorption also needs to be taken into account. Sound speed and absorption depend on several factors including salinity, temperature, and hydrostatic pressure. Here, transmission loss results for the Baltic Sea are obtained by numerical ray-tracing modeling of sound propagation in representative environments using sound speed profiles typical of each season. This results in equations predicting the upper and lower limits of transmission loss as a function of range. These limits are used in the impact zone calculations. In this way, we can estimate the upper and lower limits of the extent of the impact zones.

The absorption in the Baltic Sea is lower than that in the great oceans due to the lower average salinity of 7 practical salinity units (psu). Calculations were also made with a similar setup in more saline water, namely, the typical Skagerrak salinity of 30 psu.

In this study, we focus on one particular kind of sonar system used for antisubmarine warfare in the Baltic Sea. It is a variable depth sonar (VDS) that is typically towed behind a corvette or similar vessel and can transmit a variety of pulses at frequencies around 25 kHz. It has a source level up to 220 dB re 1 μPa at 1 m. In our modeling, we use three different pulses appropriate for operational use: a 50-ms frequency-modulated sweep from 24.5 to 25.5 kHz (FM), a 600-ms amplitude-modulated tone (CW), and a 900-ms combination of a FM part and a tone (Combo). All pulses had a center frequency of 25 kHz. The sound source was placed at the depth that gave the lowest depth-averaged transmission losses for each propagation condition.

Animals might react differently to pulses of different length. Kastelein et al. (2010) demonstrated that *P. phocoena* had a different hearing sensitivity to a 50-ms pulse compared with a 1,500-ms pulse. This is also been noticed by Southall et al. (2007), whose threshold criteria are different for pulses and so-called nonpulses. Sounds shorter than ~100 ms are categorized as pulses. By this definition, the above-described FM signal is a pulse and the CW and Combo signals are nonpulses.

2.2 Marine Mammals and Hearing

To be able to estimate the impact of a sonar on an animal, the animal's hearing sensitivity has to be known. Of the four marine mammals in the Baltic Sea, *P. phocoena* has the best hearing, with a lowest threshold of ~45–50 dB re 1 μPa between 15 and 150 kHz, but they can detect sound in the frequency range of 1–150 kHz (Lucke et al. 2009; Kastelein et al. 2010). *P. phocoena* is part of the functional group of high-frequency cetaceans as suggested by Southall et al. (2007). The three seal species are all part of the functional hearing pinnipeds in water. They can detect sound from ~100 Hz to 100 kHz at a lowest threshold of ~60 dB re 1 μPa at 20 kHz (Ridgeway and Joyce 1975; Terhune and Ronald 1975; Kastelein et al. 2009). In this study, *P. vitulina* represents the above-mentioned seal species in the calculation of impact zones. It is expected that the three species will sustain a similar impact of active sonar.

2.3 Thresholds for Reaction and Injury

A common way of describing the effects of noise on marine mammals is using the zones of influence as suggested by Richardson (1995). Different effects of noise occur in four different zones: the zone of hearing, the zone of reaction, the zone of masking, and the zone of injury. Here, we focus on the last two as impacts on behavior or a physical injury; in this case, temporary (TTS) and permanent (PTS) threshold shifts will directly affect individual animals and their survival. To set a threshold for the extent of these zones, literature data and experiments were used. Note that for the zone of reaction, in this study, we focus on the significant reactions that could have implications for the animals' survival.

In 2007, Southall et al. presented thresholds for behavioral reactions and injury to noise in marine mammals grouped in functional groups based on their hearing ability. In 2012, Finneran and Jenkins presented criteria and thresholds for the US Navy to be used in environmental impact assessments for sonar like sounds and explosions. They estimated that *P. phocoena* will most likely show a significant behavioral reaction to sonar, such as sounds at a level of 120 dB re 1 μPa. In an experiment using frequencies and signals commonly used by a sonar system in the Baltic Sea, see the description in Section 1; one *P. phocoena* showed significant behavioral reactions (irregular or increased swimming speed, increased breathing, and an increase in number of jumps) to levels of 125 dB re 1 μPa (Combo), 140 dB re 1 μPa (FM), and 155 dB re 1 μPa (CW) depending on signal characteristics (Kastelein et al. 2015a). These thresholds are higher than those suggested by Finneran and Jenkins (2012). Because a more relevant source was used in Kastelein et al. (2015a) compared with studies cited in Finneran and Jenkins (2012), the latter thresholds were used in the estimation of impact zones for a behavioral reaction in *P. phocoena*. In Kastelein et al. (2015b), the same three kinds of pulses were used on two male *P. vitulina*, but only minor reactions to the highest received level of 158 dB 1 μPa were noticed. Therefore, in this study, we used the threshold of 163 dB re 1 μPa, suggested by Finneran and Jenkins (2012), as a level to which 50% of the seals (pinnipeds in water) would show a significant reaction.

There is only one study that presents TTSs for *P. phocoena*. It was done with the use of a seismic air gun as a sound source (Lucke et al. 2009). Lucke et al. suggested a TTS in terms of a sound exposure level (SEL) of 164 dB re 1 $\mu Pa^2 \cdot s$. However, Finneran and Jenkins (2012) suggested a new weighting function and adjusted the threshold for *P. phocoena* to 146 dB re 1 $\mu Pa^2 \cdot s$ for TTS to occur at 4 kHz for a pulse. For a nonpulse, 6 dB were added to the pulse threshold, giving a threshold of 152 dB re 1 $\mu Pa^2 \cdot s$. There are no studies on PTS thresholds on *P. phocoena*, although dolphins have been shown to suffer PTS at sound levels 20 dB above their TTS thresholds. Finneran and Jenkins (2012) extrapolated this to all other functional groups, which gave PTSs for *P. phocoena* of 166 and 172 dB re 1 $\mu Pa^2 \cdot s$ for a pulse and a nonpulse, respectively.

For seals, Kastak et al. (2005) presented TTSs for *P. vitulina* to white noise at a SEL of 183 dB re 1 $\mu Pa^2 \cdot s$. This threshold is also recommended to be used by Finneran and Jenkins (2012). For PTS, it was estimated that the threshold was 14 dB above the TTS level, which is 197 dB re 1 $\mu Pa^2 \cdot s$ (Finneran and Jenkins 2012). For seals, Finneran and Jenkins did not separate a pulse and a nonpulse, although Southall et al. (2007) did. They had a 17-dB difference between a pulse and a nonpulse.

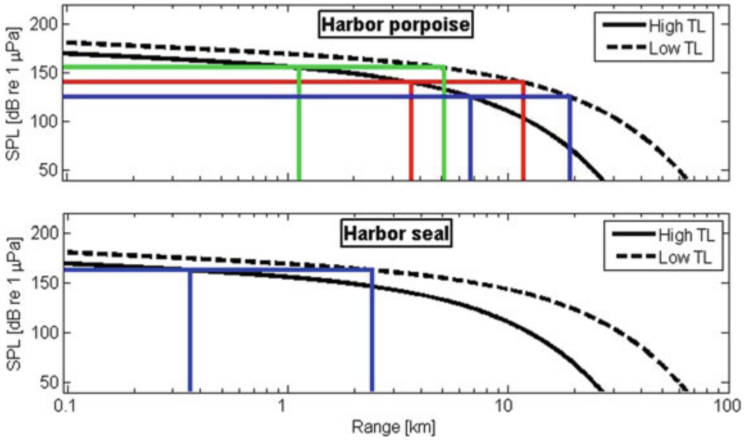

Fig. 5.1 Impact zones for significant behavioral reaction of *Phocoena phocoena* (*top*) and *P. vitulina* (*bottom*) when a variable depth sonar (VDS) transmits three different pulses: 50-ms frequency-modulated (FM) sweep (*red*), 600-ms amplitude-modulated tone (CW; *green*), and a 900-ms combination of a FM part and a tone (Combo; *blue*). All three pulses have a center frequency of 25 kHz and a source level of 220 dB re 1 µPa. Two different transmission loss (TL) models are also presented. *SPL* sound pressure level

In this study, we set the difference to 6 dB, the same as for *P. phocoena*, for the seals in the Baltic Sea. The *P. vitulina* TTS/PTS used in the modeling was 183/197 dB re 1 µPa^2·s for a pulse and 189/203 dB re 1 µPa^2·s for a nonpulse.

3 Results

Impact zones for significant behavioral reactions in *P. phocoena* were estimated to extend from 1 to 20 km around a VDS transmitting at a source level of 220 dB re 1 µPa at 1 m in typical Baltic Sea water. The extent of the impact zone depended on pulse type and transmission loss, with the Combo pulse having the greatest impact zone (Fig. 5.1). For *P. vitulina*, the impact zones were smaller, reaching ~2.5 km from the source. Note that *P. vitulina* had only one behavioral threshold regardless of pulse length. Calculations were also made with the similar setup in a more saline Skagerrak and the impact zones became shorter: 0.8–7 km for *P. phocoena* and 0.3–1.5 km for *P. vitulina*.

The impact zones for TTS for *P. phocoena* reached 3–6 km and for PTS 0.1–0.5 km from the sound source (Fig. 5.2). The impact zones for TTS and PTS for *P. phocoena* in Skagerrak were 1–2.5 km and 0.1–0.4 km, respectively. For *P. vitulina*, the risk of receiving TTS or PTS is small and the impact zones are <100 m from the sound source in both the Baltic Sea and Skagerrak.

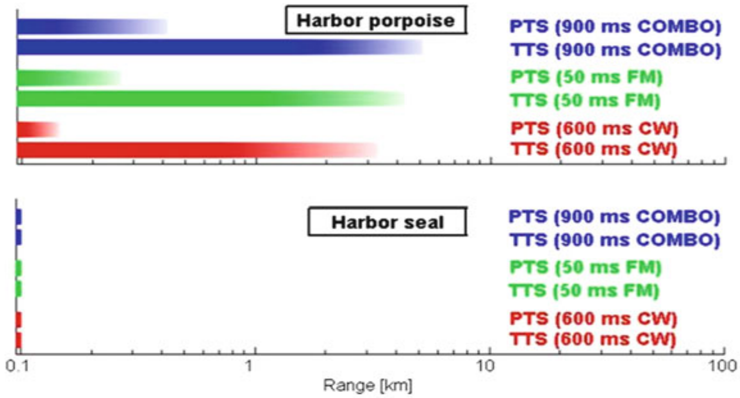

Fig. 5.2 Impact zones for temporary threshold shift (TTS) and permanent threshold shift (PTS) of *P. phocoena* (*top*) and *P. vitulina* (*bottom*) when a VDS transmits three different pulses: 50-ms FM (*red*), 600-ms CW (*green*), and 900-ms Combo (*blue*). All three pulses have a center frequency of 25 kHz and a source level of 220 dB re 1 µPa. The *shaded bars* indicate the variation in distance between high and low TL

If the source level is decreased to 200 dB re 1 µPa at 1 m, the impact zones for behavioral effects for *P. phocoena* in the Baltic Sea are decreased to 0.3–10 km and below 4 km in the Skagerrak. There is still great variability with pulse type and transmission loss. For TTS and PTS, the impact zone is <500 m in both the Baltic Sea and Skagerrak. For *P. vitulina*, the impact zones for both behavioral effects and injuries are <100 m in both the Baltic Sea and Skagerrak when the source level is decreased from 220 to 200 dB re 1 µPa.

4 Discussion

Military antisubmarine warfare sonars transmit loud pulses to detect and locate submarines. These pulses could affect marine mammal behavior and, in some cases, result in injuries in terms of TTS or PTS and, in the worst case, death. Navies in shallow seas like the Baltic Sea use different frequencies and sonar pulses compared with most other navies, and these sonar systems have rarely been studied in terms of environmental effects. These frequencies match the frequencies of best hearing in *P. phocoena* and resident earless seal species in the Baltic Sea. *P. phocoena* are shy animals, and disturbances to individuals could cause an impact on the local population, which, in the Baltic Sea, is regarded as a vulnerable population by the International Union for Conservation of Nature (IUCN).

The results presented here are based on sound propagation characteristics at typical Baltic Sea and Skagerrak locations. Although the results agree with results from field measurements, locations with significantly different environmental characteristics could display different sound propagation characteristics, resulting in impact zones greater or smaller than those presented here.

4.1 Impact Zone for Behavioral Reactions

An estimation of impact zones for significant behavioral reactions for *P. phocoena* around a VDS transmitting a 900-ms Combo pulse with a source level of 220 dB re 1 µPa at 1 m was calculated to be around 20 km with low transmission loss in the Baltic Sea, in this case, a sound channel caused by a thermocline commonly present in the Baltic Sea. This distance became shorter with higher transmission loss or if the transmission was done in more saline water like Skagerrak because more saline water has a higher absorption of sound energy. On the other hand, the absorption is frequency dependent and the use of higher frequencies in the Baltic Sea compared with LFAS and MFAS will render smaller impact zones. Moreover, because higher thresholds were used for the shorter pulses, their impact zones are smaller than those pertaining to the Combo pulses.

If *P. phocoena* are repeatedly disturbed by sonars, this will affect their ability to forage, and this is critical because they only have energy storage for a few days. In addition, a mother could abandon a calf if she is too disturbed. This would most certainly mean the death of the calf. This study used thresholds for behavioral reactions obtained in a pool experiment using one male *P. phocoena* (Kastelein et al. 2015a). The obtained thresholds for significant behavioral reactions in this study were 5–35 dB higher than the 120 dB re 1 µPa suggested by Finneran and Jenkins (2012). The use of these higher thresholds is motivated by the more accurate sound source used in Kastelein et al. (2015a) compared with the studies cited in Finneran and Jenkins (2012).

The impact zones for behavioral reactions in earless seals like *P. vitulina* are smaller than those for *P. phocoena* because the seals have poorer hearing and are less scared by noise. The ecological effects for a seal if it is scared away from important feeding grounds are not as severe because they tend to return to an area after the disturbance has stopped (Götz and Janik 2010). But if the seal is disturbed during a critical period like mating, the consequences could be serious. Seals have the advantage over *P. phocoena* in that they can go out of the water when disturbed if land is nearby. They can also surface and put their head above water to avoid the disturbance.

4.2 Impact Zone for Hearing Damage

The impact zone for TTS and PTS in *P. phocoena* to the sonar used in this study extends several kilometers from the source for all three pulses in both the Baltic Sea and Skagerrak. This is an area that is difficult to monitor, prevent animals from entering, or stopping the transmission if an animal comes within the impact zone. However, the threshold used is from only one study that used a seismic air gun as source (see Lucke et al. 2009). If sonar was used as a source and it transmitted relevant pulses, the threshold could change, which has implications for the calculation of the impact zone. The impact of multiple pulses could be more severe than that of a single pulse, but because there are no clear guidelines on how to take this into account, single-pulse SELs are used here.

If *P. phocoena* damages their hearing, it is severe because they rely on sound to forage, navigate, and communicate. For *P. vitulina*, the impact zone for TTS and PTS is only up to 100 m away from the source. This distance seams small, but today we do not know what ecological implications hearing in seals has. It is known that they use sound in social interactions, both in and out of the water.

Most recorded strandings of marine mammals have occurred in conjunction with large-scale exercises. The likelihood that single sonar transmissions will cause animals to strand is less likely. However, if an animal is close to the source, as demonstrated in this study by *P. phocoena* 3–6 km away, it could sustain temporal or permanent hearing damage, or if further away, its behavior could be altered, affecting its survival. When looking at what mitigations several countries and organizations recommend to minimize the negative effects from sonar transmissions (Dolman et al. 2009), two stand out to be more important: planning the sonar exercise in an area or at a time of year with few marine mammals and using a startup procedure to scare away animals from the impact area.

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Chapter 6
Contribution to the Understanding of Particle Motion Perception in Marine Invertebrates

Michel André, Kenzo Kaifu, Marta Solé, Mike van der Schaar, Tomonari Akamatsu, Andreu Balastegui, Antonio M. Sánchez, and Joan V. Castell

Abstract Marine invertebrates potentially represent a group of species whose ecology may be influenced by artificial noise. Exposure to anthropogenic sound sources could have a direct consequence on the functionality and sensitivity of their sensory organs, the statocysts, which are responsible for their equilibrium and movements in the water column. The availability of novel laser Doppler vibrometer techniques has recently opened the possibility of measuring whole body (distance, velocity, and acceleration) vibration as a direct stimulus eliciting statocyst response, offering the scientific community a new level of understanding of the marine invertebrate hearing mechanism.

Keywords Particle motion • Invertebrates • Laser Doppler vibrometer

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1 Introduction

The extent to which sound in the sea impacts and affects marine life is a topic of considerable concern both to the scientific community and to the general public. In addition, offshore economic interests could be at risk because of a lack of a rigorous scientific approach that would lead to precaution and excessive regulation. Marine invertebrates potentially represent a group of species whose ecology may be influenced by artificial noise. Exposure to anthropogenic sound sources could have a direct consequence on the functionality and sensitivity of their sensory organs, the statocysts, which are responsible for their equilibrium and movements in the water column. Statocyst functions generally include gravity and acceleration receptors (Maturana and Sperling 1963; Budelmann and Williamson 1994). Although statocysts have received considerable scientific attention in the past, especially in cephalopods, there is a significant gap in information on sound processing by marine invertebrates; there is still a need for definitive scientific evidence of the additional role of statocysts in low-frequency sound perception. Respiratory and electrophysiological methods confirmed cephalopod sensitivity to frequencies under 400 Hz (Kaifu et al. 2008; Hu et al. 2009), supporting the scientific consensus regarding the biological significance of the particle motion component of the sound field for these species.

Invertebrate sound receptors include a wide range of statocysts (Janse 1980; Laverack 1981), which are highly sophisticated structures that are analogous to the vestibular system of the vertebrate ear (Offutt 1970; Budelmann 1988, 1992; Williamson 1995). Vibrational and directional sensitivity of the statocyst hair cells of invertebrates, particularly of cephalopods, have been reported in the literature (Williamson 1988, 1989; Packard et al. 1990; Budelmann and Williamson 1994). Because of the high degree of development of their nervous system, characterized by the large size of the neurons, cephalopods were often used for neurophysiology studies (Bleckmann et al. 1991; Budelmann et al. 1995) to determine hearing thresholds. Here, we concentrate on these species to illustrate the general sound perception of marine invertebrates.

Cephalopod statocysts show a variety of forms, but they can be grouped into three main types (Budelmann 1988) depending on species (nautiloids, octopods, and decapods). They usually include two categories of receptor systems, the macula-statolith system and the crista-cupula system. The macula-statolith system informs on changes in the position according to gravity and linear acceleration, whereas the crista-cupula system indicates changes in angular acceleration. This presents analogies with the vestibular system of the vertebrate inner ear (Colmers 1977). However, unlike ciliated cells of vertebrates, the cephalopods' statocyst sensory cells carry kinocilia. Microvilli are found surrounding the base of the kinocilium. Kinocilia and microvilli form elongated bundles. Each bundle represents a single hair cell. Every hair cell is arranged in line with an adjacent hair cell in both the crista and macula (Budelmann et al. 1973) and is unidirectional morphologically and physiologically polarized. Adjacent accessory structures (statolith, statoconia, cupula) are responsible for the sensory perception. When there is a stimulus, tiny deflations occur in the hair bundles, resulting in cell body depolarization and subsequent transmission of the information to the sensory nervous system.

At central nervous system level, the sensory input of the statocysts is used to regulate a wide range of behaviors, including locomotion, posture, control of eye movement, and body coloration pattern. In addition, there is now evidence the statocysts are also responsible for the reception of low-frequency sound waves (Kaifu et al. 2008; Hu et al. 2009; André et al. 2011; Solé et al. 2012). The sensory epithelia of the gravity receptor system, in resemblance to the vertebrate auditory apparatus (Puel et al. 2002), have secondary sensory hair cells that are unidirectional morphologically and physiologically polarized, first-order afferent neurons, and efferent nerve fibers. The synaptic arrangements are as complex as those in the vestibular maculae (see, e.g., Sans et al. 2001); the outputs of several hair cells converge onto an afferent neuron and the output of a single hair cell diverges onto several afferent neurons. The efferent fibers of the statocyst terminate on both hair cells and the axons of afferent neurons (Budelmann et al. 1987).

Although little is still known about the sound perception mechanism in invertebrates (Packard et al. 1990; Bleckmann et al. 1991; Bullock and Budelmann 1991; Kaifu et al. 2008; Hu et al. 2009), recent behavioral and electrophysiological experiments conducted on cephalopods confirmed the species sensitivity to frequencies under 400 Hz (Kaifu et al. 2007, 2008; Hu et al. 2009; Mooney et al. 2010) and the important role of statocysts in sound reception (Kaifu et al. 2008; Hu et al. 2009; André et al. 2011; Solé et al. 2012). Although there is little uncertainty regarding the biological significance of particle motion sensitivity versus acoustic pressure, the question is how particle motion is detected and transmitted to the statocysts from any acoustic source.

It was suggested that the particle motion can encompass the whole body of cephalopods and cause it to move with the same phase and amplitude; the statolith organs would then be stimulated by whole body displacements (Packard et al. 1990; Kaifu et al. 2011). The statolith organs are inertial detectors in which a calcareous statocyst is attached to the sensory hair cells. When an animal accelerates, the statolith moves, bending the sensory hair cells. Thus, the statolith could serve as a receptor of kinetic sound components (Packard et al. 1990; Kaifu et al. 2011). However, to the best of our knowledge, there has been no study that showed that the whole body can vibrate when stimulated by underwater sound in aquatic invertebrates or may be neither in aquatic vertebrates such as fishes.

The availability of novel laser Doppler vibrometer techniques has recently opened the possibility of measuring whole body (distance, velocity, and acceleration) vibration as a direct stimulus eliciting statocyst response, offering the scientific community a new level of understanding of the marine invertebrate hearing mechanism. These techniques have already been applied to several species such as amphibians, reptiles, and crustaceans (Hetherington and Lindquist 1999; Hetherington 2001). Although some preliminary experiments have been conducted using the laser

Doppler techniques, no measurement of the whole body vibration induced by underwater sound was performed. Here we present a series of measurements conducted in controlled experimental conditions aimed at determining if cuttlefish and scallop bodies vibrate when stimulated with pure-tone sounds.

2 Methods

2.1 *Controlled Exposure Experiment Conditions*

Controlled exposure experiments were conducted using the experimental setup shown in Fig. 6.1. The equipment was placed inside a closed room of dimensions 4.2×3.2×2.7 m. The room contained other furniture and objects that affected the acoustic field inside the room. The water tank (80×30×40 cm) was placed on top of a layer of foam on a table. The target (reference reflective objects, cuttlefish, and scallops) was placed on one side of the tank. The target was suspended with an elastic string from a wooden pole that was placed over the tank, supported on both sides by a tripod. The pole was not in contact with the tank. The target was positioned ~20 cm below the water surface. The vibrometer (Polytec OFV-505 with OFV-5000 controller) was placed on an absorbing foam layer and was never moved during the experiment. The beam angle had to be adjusted with each target, together with the orientation of the pole, to ensure a proper reflection. For animal targets, a small flat piece of aluminum foil attached to the body was used as a reflector. On the other side of the tank, a loudspeaker was suspended over the water supported by two tripods; no part of the loudspeaker setup was in direct contact with the tank or pole. The pure-tone signals were generated by an Agilent wave generator and passed on to the loudspeaker through a commercial amplifier. Changing the voltage level of the wave generator, keeping the amplifier at a fixed amplification setting, varied the source sound level.

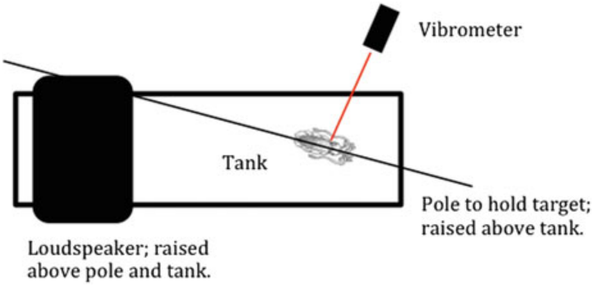

Fig. 6.1 Experimental setup for the vibration measurements

Table 6.1 Vibration of the laser Doppler vibrometer

Vibration laser acceleration (dB re 10^{-6} m/s^2)			
	60 Hz	120 Hz	320 Hz
x-axis	70.2	92.0	104.7
y-axis	70.9	76.8	97.7
z-axis	82.4	96.4	113.1

The *x*-axis was in the direction of the measurement

Table 6.2 Acceleration of targets at different frequencies

Acceleration (Hz)													
	60	80	100	110	120	130	150	170	190	240	320	350	360
Bar	101	96	110	113	98	104	115	108	105	113	136	113	119
Scallop	100	97	109	113	96	102	109	118	95	110	136	114	115
Cuttlefish	103[a]	100[a]	114	114	106	106	116	112	107	115	138	108[a]	115[a]
Tape	106	104	116	118	109	107	114	112	108	119	140	115	117

Values are peaks in dB re 10^{-6} m^2/s^4/Hz

[a] Only one measurement was used for cuttlefish at those frequencies; the other values are average measurements from two animals

2.2 *Targets*

The invertebrate representative targets that were used in this experiment were cuttlefish and scallops, and a small dense metal bar and a small piece of reflective tape were chosen as reference targets because it was expected that, due to density differences, the scallops would vibrate at a speed closer to the metallic bar while the cuttlefish, because of its neutral buoyancy, would behave more like a freely floating small tape when exposed to sound. The animals were anesthetized during the exposure to avoid movement. When long exposure times were used, the animal awaking time was monitored and the experiments were resumed after the animal was put back to sleep.

The laser configuration was calibrated using a vibration source working at 160 Hz and 9.8 m/s^2 (140 dB re $a_o = 10^{-6}$ m/s^2 [acceleration reference level]). It was placed at the other side of the tank and measured through both tank walls (see Table 6.1). The vibration of the laser itself was measured as well for three frequencies of interest. The vibration measurement of a target was considered reliable if it was at least 10 dB higher than the vibration of the laser.

The consistency of the measurements and the effect of the precise position of the target were tested by measuring the inanimate targets at slightly different positions. The scallop and especially the cuttlefish were much larger than the test targets and measuring their vibration only at a single spot was not expected to be representative for the whole body.

Targets were never moved between measurements of different frequencies, although sometimes the focus of the laser beam had to be adjusted to ensure good reflection. Measurements were always made in a series of two, moving from the lowest to the highest frequency, exposing the target for at least 16 s, and then repeating the sequence from the lowest frequency.

2.3 Choice of Frequencies

A first series of measurements was conducted with a wide range of frequencies (from 60 to 360 Hz; see Table 6.2), together with corresponding sound pressure level (SPL) measurement. The difficulty of working with live animals required the selection of fewer frequencies for the final round of experiments. An obvious frequency to use appeared to be 320 Hz because it induced a large response of all targets. Two other frequencies, 60 and 120 Hz, were selected for further experimentation because of their proximity to the European Union Marine Strategic Framework Directive (MSFD) indicators that are being used to evaluate noise pollution (good environmental status [GES] indicator 11.2; van der Graaf et al. 2012).

2.4 Cuttlefish Body Response

Working with a live animal is difficult, especially for long exposure, due to the need for constant monitoring and pausing the experiment to renew the anesthesia. Continuing the experiment with the exact same target position and laser orientation was often impossible. The state of the animal can normally be monitored while taking measurements. We conducted controlled exposure experiments with both dead and live animals to estimate variations and validate results obtained from the measurements.

3 Results

3.1 Frequency Response

Table 6.2 shows the target accelerations at all measured frequencies.

3.2 Effect of Position on Measurements

At each position, multiple measurements showed very consistent results with identical peak levels. Then, repositioning the object, which required slight focus adjustment of the vibrometer beam without moving the vibrometer itself, led to considerable differences in some cases. At 60 and 120 Hz, some positions were quite close to the vibration levels of the vibrometer; this was not unexpected for the bar. After repositioning, the measured levels were above the self-vibration. At 320 Hz, all measurements were consistent and well above self-vibration.

3.3 Comparison of Dead to Alive Animals

A slow-frequency oscillation corresponding to the breathing rate of the animal was monitored during the measurements of live individuals. The magnitude of the oscillation may be dependent on the state of anesthesia, but this breathing motion did not affect the acceleration measurement induced by the acoustic wave. The dead animal measurements were all identical between exposures, whereas the live animal measurements showed differences not only between animals but also between exposures of the same animal. The measurements of the dead animal, however, fell in the same acceleration range as those of the live animals or what was explained by a change in position.

3.4 Body Vibration

Figure 6.2 shows the results of the four targets (reference targets and animals) at the three chosen frequencies.

4 Discussion and Conclusions

There was little doubt that marine invertebrates were sensitive to (i.e., perceive) low-frequency sounds and that this sensitivity was not directly linked to sound pressure but to particle motion. The missing component in the analysis was the demonstration that the statolith would act as an harmonic oscillator, excited when the whole animal body was vibrating when exposed to sound waves.

The differences of the laser Doppler acceleration measurements (see Table 6.1) with the target vibration measurements (Fig. 6.2) allow us to conclude that the exposure to sound has elicited the cephalopods and scallops whole body vibration, confirming the initial hypothesis that particle motion can encompass the whole body of cephalopods and cause it to move with the same phase and amplitude (Packard et al. 1990; Kaifu et al. 2011) as well as consolidating the use of laser Doppler techniques in underwater bioacoustics studies.

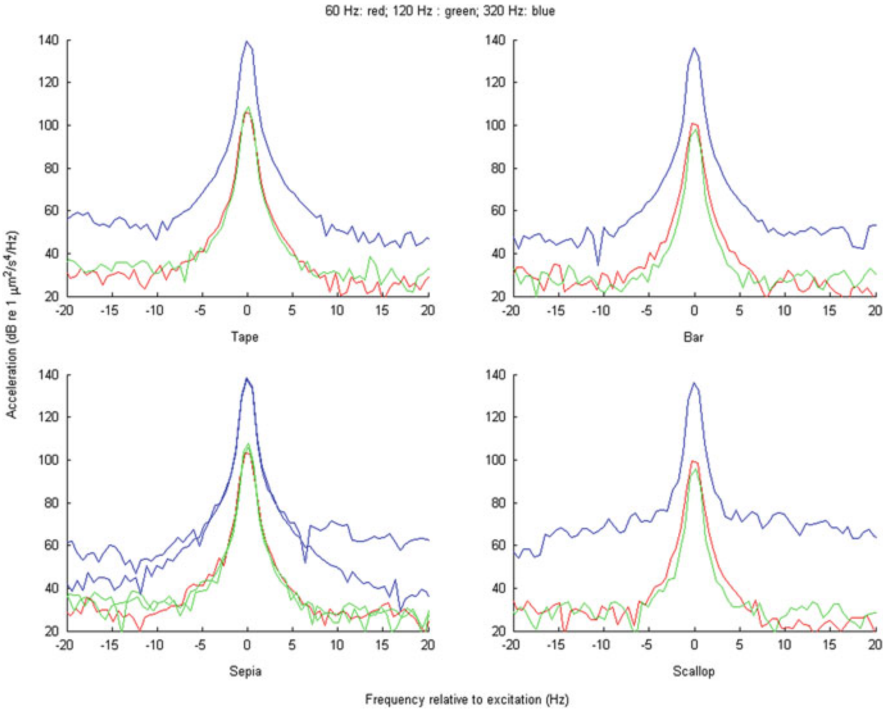

Fig. 6.2 Laser Doppler target acceleration measurements at the three chosen frequencies

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Chapter 7
Functional Morphology and Symmetry in the Odontocete Ear Complex

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Abstract Odontocete ear complexes or tympanoperiotic complexes (TPCs) were compared for asymmetry. Left and right TPCs were collected from one long-beaked common dolphin (*Delphinus capensis*) and one Amazon River dolphin (*Inia geoffrensis*). Asymmetry was assessed by volumetric comparisons of left and right TPCs and by visual comparison of superimposed models of the right TPC to a reflected mirror image of the left TPC. Kolmogorov–Smirnov tests were performed to compare the resonant frequencies of the TPCs as calculated by vibrational analysis. All analyses found slight differences between TPCs from the same specimen in contrast to the directional asymmetry in the nasal region of odontocete skulls.

Keywords Odontocete • Sound reception • Vibrational analysis • Tympanoperiotic complex

1 Introduction

Cetaceans have become secondarily aquatic. Because light penetrates poorly in water, hearing has become an acute sensory system in cetaceans, a means of collecting information about the world that is particularly suited to water. Underwater sound travels more than four times faster than in air and can cross ocean basins. The toothed whales have evolved a sophisticated underwater biosonar system that can provide information during environmental darkness, penetrate into or through some objects, and reach beyond the normal visual range. This biosonar system can be subdivided into three parts: the sound production and reception apparatuses and

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the central nervous system components that integrate the other subsystems and interpret the results. The odontocete biosonar sound production and reception subsystems are of particular interest to morphologists because odontocetes have evolved a set of structures that solve the unique hydrodynamic and pressure constraints of operating underwater while diving. In contrast, echolocation is not unique to odontocetes, having evolved multiple times among nonaquatic vertebrates like bats, shrews, tenrecs, and swiftlets.

In odontocete echolocation, sound is produced by vibrating specialized pairs of tough phonic lips a few centimeters underneath the blowhole (Cranford et al. 1996, 2011). Depending on the species, biosonar beam formation and sound reception are accomplished by combining anatomic geometry with various acoustic mechanisms (Cranford et al. 2014). For example, the impedance mismatch between air-filled sinuses and dense connective tissues, or bone cause sound to be reflected while the refractive properties of specialized acoustic fats in the forehead and lower jaws can result in focusing (Barroso et al. 2012; Cranford et al. 2014). These tissue properties and the anatomic geometry serve to produce a concentrated forwardly projected beam from the melon and provide a mechanism to focus the returning echoes on the tympanoperiotic complex (TPC; Krysl et al. 2006). The odontocete peripheral sound reception apparatus is analogous to the outer ear or pinna of terrestrial mammals, once thought to include an "acoustic window" over the thinned translucent lateral wall of the mandible (Norris 1968). We now think that sound enters the odontocete head through a variety of the soft tissue pathways that are currently incompletely understood. Some of the pathways include lateral portions of the throat as well as specialized bodies of "acoustic fat" that carry sound to the TPC (Cranford et al. 2010; Cranford and Krysl 2012). One anatomic characteristic thought to be central to the biosonar system is asymmetry (Cranford et al. 1996, 2011; Fahlke et al. 2011).

There are three types of bilateral asymmetry in vertebrates. We will not be concerned with fluctuating asymmetry or antisymmetry here. Directional asymmetry is characterized by one side always being larger than the opposite side. When it occurs, directional asymmetry has been shown to be functionally significant and is normally small in magnitude. However, the directional asymmetry found in the nasal anatomy of the sound production system in all odontocetes is one example of large-magnitude directional asymmetry (Cranford 1988, 1992). To investigate the degree to which directional asymmetry might contribute to directional cues in odontocete sound reception, we compared both left and right TPCs for two odontocete specimens that are phylogenetically distant from one another (McGowen et al. 2009).

2 Materials and Methods

The left and right TPCs from one long-beaked common dolphin (*Delphinus capensis*), hereafter referred to as *Delphinus*, and one Amazon River dolphin (*Inia geofferensis*), hereafter referred to as *Inia*, were collected from the California

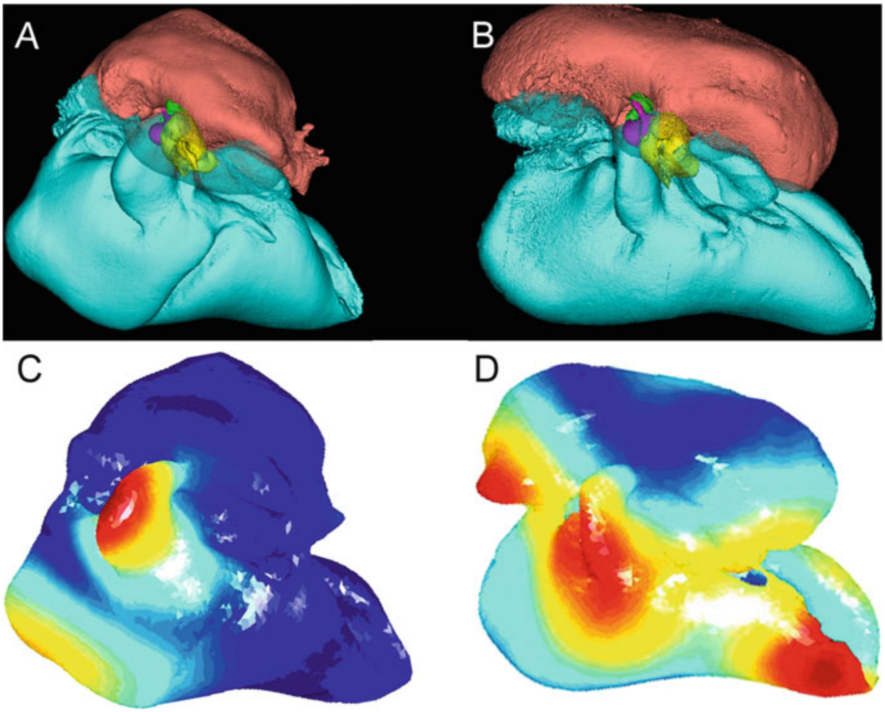

Fig. 7.1 Right lateral views of tympanoperiotic complexes (TPCs) from *Inia geofferensis* (**a**) and *Delphinus capenis* (**b**). In these views, the tympanic and periotic areas are transparent, making the ossicles visible. Motion maps of the 14th resonant-frequency modes for *Inia* (**c**) and *Delphinus* (**d**) TPCs. *Warm colors* indicate larger displacements and greater oscillatory motion

Academy of Sciences and scanned using high-resolution computed tomography (MicroCT). We used these specimens to assess within-individual TPC asymmetry. All four TPCs, one pair from each specimen, were scanned at 45-μm slice thickness. The MicroCT scans were segmented by an experienced technician to define the boundaries of various anatomic structures (Fig. 7.1a, b) using Analyze 10.0 visualization software (Robb 2001). Volumetric comparisons of the segmented TPCs were performed by summing all the image voxels from each TPC.

Vibrational analyses were performed in MATLAB (Mathworks 2012) using a custom MATLAB toolkit BioImageFE. The MicroCT data were imported into MATLAB and used to generate binary images using the radiodensity Hounsfield units that correspond to bone. These preprocessed images were then used to generate a 3-dimensional (3-D) finite-element mesh, initially at native MicroCT resolution such that each 3-D voxel has its own hexahedral element. To facilitate efficient analysis, the meshes were resampled and coarsened using built-in algorithms to lessen surface complexity. Native resolution was preserved for a manually determined radius around the ossicles to ensure accuracy of the vibrational analysis results (Fig. 7.2b). This prepared mesh was then used to perform a normal mode or

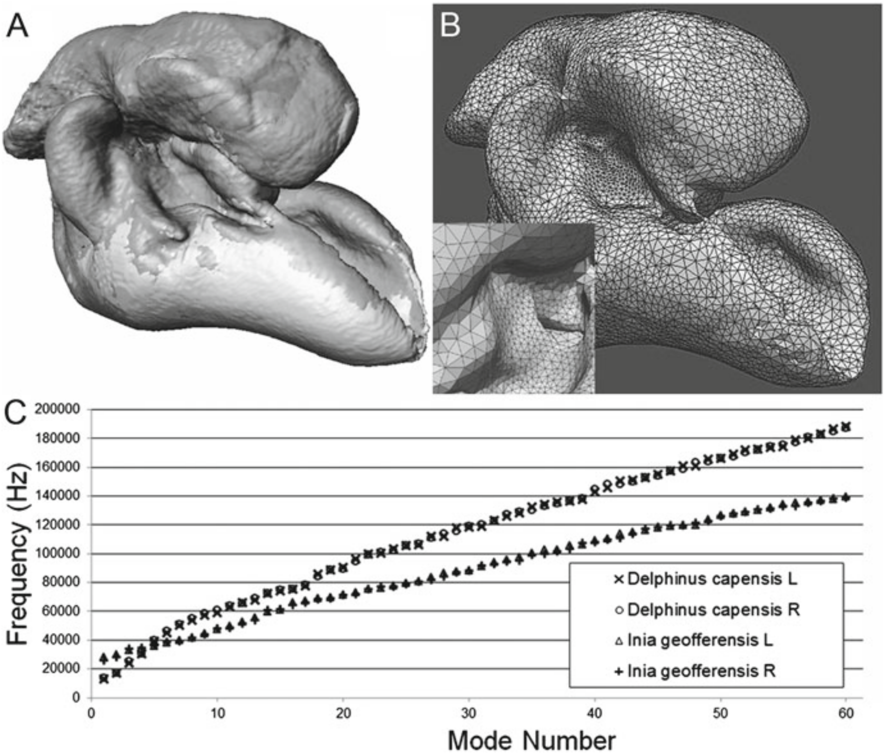

Fig. 7.2 (**a**) Superimposition of the reflected left TPC and the right TPC from *Delphinus*. (**b**) Mesh of the right TPC from *Delphinus*. Note that the ossicles are meshed at the maximum resolution (*inset*) (**c**) Resonant or "natural" modes of vibration plotted against acoustic frequency for the left and right TPCs of each individual specimen of *Inia* and *Delphinus*. Note that the left and right TPC modes are nearly identical

free vibration analysis of the TPC meshes. The Poisson ratio of TPC bone was applied from the results of a previous study (Currey 1979). The first 60 natural resonant frequencies or modes (i.e., Eigenmodes or Eigenfrequencies) were calculated for the left and right TPCs of both specimens, sufficient to cover the reported range of frequencies measured behaviorally for *Inia* (Jacobs and Hall 1972) and physiologically for *Delphinus* (Popov and Klishin 1998). These modes and their frequencies are plotted in Fig. 7.2c. Kolmogorov–Smirnov nonparametric pairwise tests performed within the R statistical programming environment were used to determine if there was a significant difference between the modal frequencies of left and right TPCs from the two dolphin species (R Development Core Team 2013).

Analyze software was also used to generate 3-D surface files, which were viewed using Landmark software (Wiley et al. 2005) to assess differences in shape visually. Left TPCs were reflected about the *z* axis to directly compare the shapes of the left and right TPCs from the same individual. A series of homologous landmarks were selected and used as points of reference with which the left (mirror image) and right TPCs from each individual dolphin were aligned and superimposed for viewing the morphological differences (Fig. 7.2a).

3 Results

Volumetric comparisons of the left and right TPCs of *Delphinus* displayed a difference of 4.1481% (43,053,540 and 41,303,913 voxels, respectively). In *Inia*, the left and right TPC disparity is a mere 0.7077% (84,491,840 and 83,895,973 voxels, respectively). These results indicate that, for all practical purposes, the TPCs are volumetrically symmetrical within each individual. It is also interesting that the minute asymmetry detected by our high-resolution measurement tools show that the left TPC was slightly larger than the right TPC.

The left and right TPCs of both specimens also showed close correspondence in the vibrational analysis results for each individual. For all modes, the frequencies of left and right TPCs were virtually identical by visual inspection when plotted (Fig. 7.2c). Conversely, there was a large difference in the plots between species, indicating that differences caused by minute anatomical asymmetry in the TPC pairs for each individual were dwarfed by functional differences between the species. This was confirmed by Kolmogorov–Smirnov tests of these modal frequencies. Pairwise tests of the left and right TPCs for *Delphinus* gave $D=0.0333$ and $P=1$, indicating no significant difference. Repeating the test with the left and right TPCs from the *Inia* specimen returned the same results: $D=0.0333$ and $P=1$. Conversely, pairwise tests of the left TPCs of *Inia* and *Delphinus* gave $D=0.35$ and $P=0.001171$, indicating that the two species have significantly different vibrational characteristics that are evident in the morphological differences (Fig. 7.1a, b).

When we reflected the left TPC across the z axis (mirror image) and blended the images using Landmark software, we found that the mirror image left TPC and the right TPC appeared to correspond so closely that only a small veneer of difference can be seen (Fig. 7.2a). Rendering the TPCs transparent also allowed for direct comparison of the TPCs. When one TPC was “outside” another, it was universally the case that the “inner” TPC lay just underneath. Although correspondence was universally very close for both specimens, a few bony protrusions along the junction between the tympanic and periotic bones could be found on close inspection. These protuberances were small and accounted for 0.025% of the total volume of each TPC.

4 Discussion

The measurements and calculations in this study indicate a general lack of asymmetry, at least in the bony components of the TPC. The volumetric measurements and visual inspection of the superimposed (mirror image) anatomy displayed only slight differences, a maximum of around 4%. Statistical tests of the vibrational analyses suggest that this difference is of negligible functional significance with respect to the resonant frequency modes. For the purposes of sound reception, it appears that the TPC is essentially bilaterally symmetrical. This may be critical for the TPC as a functional component of the odontocete sound-reception apparatus.

However identical the TPCs may be, it is important to note that the findings of this study do not mean that there is no asymmetry in the sound-reception system. It is possible that differences in the position or orientation of the TPC within the skull exist and we would not have detected this with our methodology. Asymmetry could also exist in and around the soft tissues of the ear and peripheral auditory system or in the properties of the acoustic fats that serve to guide sound to the TPC (Cranford et al. 2008a, 2010). In fact, a recent study (see Chapter 70 by Krysl and Cranford) modeling the head-related transfer function within the soft tissues of *Delphinus* indicates that this may be the case.

Our group has studied the sound-reception system in several odontocete species by comparative anatomy and finite-element modeling (Cranford et al. 2008a, b, 2010). The finite-element modeling system we built has recently been validated (Krysl et al. 2012; Cranford et al. 2014), meaning that simulation results do match experimental results in test cases.

Previous work has shown that the primary pathways for sound are from in front of the animal, underneath the lower jaw, and then posteriorly through the lateral aspects of the gular anatomy to the ears. Studies have also suggested that the pathways to the ears differ depending on frequency (Cranford and Krysl 2012). Because the course and location of the pathways are different depending on the frequency, the position of the sound source may have a dramatic effect on the amplitude and spectrum of the sound that reaches the TPC by any particular pathway. This may have implications for the large volume of work that has been conducted to measure hearing parameters in dolphins using "jawphones" over the last 20 years, particularly when policy and regulatory decisions are based on it. A few studies have attempted to map "jawphone" placement to hearing sensitivity (Møhl et al. 1999; Brill et al. 2001), but the details of the mechanisms and pathways produced by these devices are still incomplete.

5 Conclusions

The results of this study suggest that there is little significant functional or structural difference between the TPCs within the same individual dolphin and that this pattern exists in at least these two distantly related taxa.

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Chapter 8
A Low-Cost Open-Source Acoustic Recorder for Bioacoustics Research

John Atkins and Mark Johnson

Abstract Acoustic recorders are the primary tool used in marine bioacoustics; however, available devices are either expensive or lack self-calibration capabilities that are critical for high-quality measurements. Moreover, the software used in proprietary designs can be inflexible and may involve unknown processing steps. To address this, we have designed a miniature low-cost yet high-performance acoustic recorder that features open-source hardware and software. Circuitry is included for self-calibration, making it possible to evaluate device performance in situ. Our intention is that the design will develop in conjunction with the needs of the bioacoustics community.

Keywords Acoustic • Recorder • Design • Noise

1 Introduction

The wide frequency range of underwater sounds together with the large variety of conditions in which measurements must be made mean that there is no one-size-fits-all solution for sound recording. In some applications, high performance or reliability are paramount, whereas other cases call for low-cost, easily deployed systems. Notwithstanding this broad range of performance criteria, underwater sound recordings are increasingly being used to inform decisions with economic or legal implications. Monitoring of noise produced by offshore construction activities is required by law in some countries (de Jong et al. 2011) and long-term acoustic measurements are now required throughout Europe to meet the standards for good environmental status (European Commission 2008). Underwater noise measurements

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are also an historical resource that is increasingly used to establish the extent of human-caused changes in aquatic environments (Andrew et al. 2003; McDonald et al. 2006). However, apart from some specific sound sources, there are no international standards for underwater sound measurements (de Jong et al. 2011). In lieu of such standards, it is important that sound recordings be made with the best possible fidelity and that they be preserved with complete details of the way in which they were obtained. Underwater recordings are generally made with commercial or custom-designed systems for which the performance and processing steps are not described openly, making it difficult to compare measurements made by different systems. Because the quantity of data collected by these systems is increasing exponentially, there is an urgent need for the marine bioacoustics community to define the best practice in underwater sound measurements and reporting. Such a standard should establish a minimal set of performance attributes such as sensitivity, frequency response, and system noise floor, which must be characterized and preserved with each recording. As a step toward this goal, we have developed a low-cost, rugged sound measurement device that has an extensive range of self-calibration capabilities. Importantly, the hardware and software design of the device are completely open, potentially making this implementation a reference platform on which to develop standards. Being open, the design can be adapted to a range of activities including noise monitoring, detection and abundance estimation of marine mammals, studies of sound output, and phonotaxis in fish and geophysical research.

The objective of this paper is twofold: to review some of the desirable attributes and performance-limiting factors in underwater sound recorders and, in light of these, to describe the decisions made in designing the new recorder. Because these issues apply to all sound recorders, it is hoped that the discussion may offer a starting point in assessing what constitutes the best practice in the design of underwater acoustic devices.

2 Design of Underwater Sound Recorders

Our objective has been to produce a high-performance but easy-to-use device at a low cost. Here we discuss four fundamental design issues and their impact on this objective: self-noise, calibration, metadata, and packaging.

2.1 Self-Noise

The self-noise of a recorder determines its utility for measuring ambient levels or for detecting weak signals from distant animals. Ambient levels vary widely in the ocean but Table 8.1 gives rough estimates of the lowest expected levels in deep water based on the Wenz curves (Urick 1983; McDonald et al. 2006).

Table 8.1 Comparison of ocean ambient noise with the noise floor of the Open Recorder

Frequency	Lowest ambient noise (dB re 1 μPa rms/$\sqrt{}$Hz)	Equivalent preamplifier input level (nV rms/$\sqrt{}$Hz)	Open recorder self-noise (nV rms/$\sqrt{}$Hz)
100 Hz	51	50.1	
300 Hz	48	35.4	6.3
1 kHz	44	22.4	3.3
3 kHz	37	10.0	2.5
10 kHz	27	3.2	2.3
30 kHz	20	1.4	2.2

Equivalent preamplifier input level was made with a −197 dB re 1 V/μPa hydrophone element. *rms* root-mean-square

A number of circuits contribute to the self-noise of a recorder and the combined effect of these is expressed as the referred-to-input (RTI) voltage noise. The RTI self-noise can be compared with the ambient-noise level by multiplying the latter by the hydrophone sensitivity. Wideband hydrophones used in underwater recorders are typically made from end-capped rings or spheres of piezoelectric ceramic, with the former being both more economical and more sensitive for a given dimension. The sensitivity of a thin end-capped ring is roughly proportional to its diameter, but the maximum usable frequency varies inversely with diameter, placing an upper limit on sensitivity (Rittenmyer and Schulze 1999). To overcome this, several rings are often stacked and wired in series. To avoid the directionality of a long thin hydrophone, short rings must be used, leading to reduced capacitance and an inevitable increase in self-noise at low frequencies. Thus there are a number of trade-offs in hydrophone design that limit sensitivity. The Open Recorder uses two 10-mm-diameter rings in series, giving a frequency response to 70 kHz and a sensitivity of about −197 dB re 1 V/μPa. Using this figure, the preamplifier input levels equivalent to the lowest expected ambient noise are given in Table 8.1. To be able to measure these levels, the recorder self-noise must be at least 6 dB lower.

In a well-designed acquisition system, the preamplifier noise dominates the RTI noise because noise contributions from the subsequent sections are effectively reduced by the gain of the preamplifier. Hydrophones have a high impedance at low frequencies and so require a field effect transistor (FET) preamplifier both to achieve a low-frequency response and to minimize current noise. Careful design is required to obtain low noise with these devices at a moderate power consumption (Allman 1968). The Open Recorder uses discrete FETs to achieve a RTI noise of ~2.3 nV/$\sqrt{}$Hz (an equivalent acoustic noise level of 24 dB re 1 μPa/$\sqrt{}$Hz) at 10 kHz with a power consumption of 3.5 mW (Table 8.1). This noise level is sufficient to measure the lowest ocean ambient noise up to ~8 kHz. Beyond this frequency, the self-noise will dominate in quiet locations. By way of comparison, the popular High Tech HTI-96-MIN hydrophone used in several commercial recorders has a self-noise floor of 42 dB re 1 μPa/$\sqrt{}$Hz above 100 Hz (see http://www.hightechincusa.com/96_MIN.html), which is some 15 dB above the lowest ambient noise at 10 kHz.

2.2 Calibration and Characterization

Three types of information are needed to characterize a sound recorder: its absolute sensitivity, bandwidth, and self-noise. Sensitivity is usually measured in a tank equipped with a sound source by comparing the received levels against a reference hydrophone. Because a large tank is required for low-frequency measurements, the sensitivity is usually measured at >10 kHz and extrapolated to lower frequencies. Hydrophone materials such as Navy IV are relatively stable and so, after initial factory calibration, the main reason to measure sensitivity is to detect a damaged element or a change in the audio circuit characteristics. A pistonphone provides a convenient way to check for a change in sensitivity at a single frequency before deploying a recorder, and the Open Recorder's hydrophone and surrounding protective cage have been designed to mate with a standard pistonphone via a coupler. The response of a hydrophone element at frequencies well below its resonance can be predicted reasonably reliably from a single-frequency pistonphone measurement. However, the response of the acquisition channel may vary more widely with frequency because it includes low- and high-pass filters. The system frequency response can be measured by injecting a known signal into the audio input, but this normally requires disconnecting the hydrophone. The Open Recorder includes an audio output channel specifically for this purpose, allowing an arbitrary calibration signal to be injected directly into the hydrophone circuit for in situ frequency-response measurements. This test is performed automatically at the beginning of each recording, and the data are included with the recording. This self-calibration method can also be used to detect breakage of a hydrophone element during a deployment because any change in the capacitance of the element will cause a step-change in the system frequency response.

The self-noise of a recorder is usually estimated from the signals recorded in air in a quiet environment, but it can be difficult to obtain sufficient quiet, especially at low frequencies. An alternative approach is to remove the hydrophone element and replace it with a capacitor that is electrically equivalent but acoustically insensitive.

The Open Recorder includes an electronic switch that bypasses the hydrophone to enable in situ self-noise measurements. This is done automatically at the beginning of each recording for a period of 2 s and the noise floor information is kept with the recording, making it straightforward to plot received level curves with the contemporaneous system noise.

2.3 Metadata

Almost as important as the sound recordings themselves is information about how the recordings were obtained. These metadata should define the recording equipment (its design, configuration parameters, serial number, and calibration); the location, depth, and time at which the recordings were made; and any relevant ancillary information such as the water temperature and salinity that could help define the listening conditions. Unfortunately, there is no standard way to describe and store metadata for underwater sound recordings. Moreover, complete metadata information may not be available for recorders that include proprietary processing steps.

A vast majority of underwater sound data is kept in WAV format files because of the simplicity of this format and the large number of software applications that support it. Although some metadata can be incorporated into WAV files, it is awkward to do so and is often not supported by software. An alternative to the WAV file is the format used by the open-source FLAC lossless compressor. This format is widely supported and allows insertion of metadata but, unfortunately, only allows a single block of metadata per recording, making it difficult to include time-varying information such as the depth or location of a moving platform.

The Open Recorder uses a related but simpler lossless compression scheme designed specifically for underwater sound data (Johnson et al. 2013). The open file format used by this compressor includes provision for metadata collected throughout a deployment and so offers a single file solution for sound data archiving and exchange. Being an entirely open design, the metadata reported by the recorder includes a complete description of the sound-processing steps performed by the device. Metadata is stored in a descriptive XML format embedded in the sound file, making it machine readable and searchable. The sound files can be unpacked to separate WAV and text files for use with standard analysis tools at any time.

2.4 Packaging

The packaging of a recorder has a major impact on its performance, cost, and durability. For large deployments, the recorder may represent a small fraction of the total deployment cost, making an expensive housing acceptable. But for many applications, a small, lightweight, and low-cost housing is advantageous. Air-filled pressure housings are normally used for recorders and are convenient for accessing batteries and data but are both expensive and critically reliant on expert assembly to avoid the ingress of water. For recorders using solid-state memory, another approach is to use a pressure neutral design in which a plastic housing is filled with an incompressible substance such as oil or a re-enterable polymer. Pressure is transferred to the inside of the housing via a diaphragm in the wall, thereby avoiding the mechanical stress of an air-filled housing. This allows the housing to be constructed of low-cost materials such as thermoplastics and still be rated for ocean depths.

A caveat of this approach is that the contents of the housing are subjected to ambient pressure and must therefore be pressure tolerant.

Fortunately, passive components such as capacitors and resistors are available in ceramic forms that are inherently pressure tolerant. Integrated circuits are also suitable, with few exceptions. Components that require more attention include batteries and crystal oscillators, but pressure-tolerant options are available.

The Open Recorder uses a pressure neutral housing constructed from rigid PVC plastic and pressure equalization is achieved by means of a flexible polyurethane diaphragm molded over the housing. By filling the housing with mineral oil and eliminating as much air as possible, a small deflection of the diaphragm is sufficient for equalization. Access to the housing contents has been made unnecessary by incorporating a rechargeable battery and a wet electrical connector for battery recharging and USB data offload. Eliminating the need to open the housing has the additional and important benefit of reducing the likelihood of flooding, thereby improving durability.

3 Conclusions

It is critical that the marine bioacoustics community take an active role in defining standards and best practice for underwater sound measurements. These definitions should include requirements for calibration of the sensitivity, frequency response, and noise floor of the equipment and should require that complete information about the recording process be included in the metadata with each recording. But these requirements may not be easily achieved with currently used systems and file formats. Commercial recorders do not generally support self-calibration and may include proprietary processing steps that cannot be defined in the metadata. Moreover, the widely used WAV file format does not facilitate colocation of the metadata and audio data. As a step toward overcoming these issues, we have developed an open source, low-cost, high-performance sound recorder. It features in situ calibration capabilities and uses an audio output file format with flexible support for metadata. The use of a pressure neutral housing reduces the cost of the device and makes it “student proof.” Most importantly, the design of the recorder is completely open and so can be improved on and adapted to other applications. Our intention is that the device will make high-quality underwater measurements accessible to a wider community of researchers and will provide a well-understood performance benchmark against which to develop standards.

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Chapter 9
Assessment of Impulsive and Continuous Low-Frequency Noise in Irish Waters

Suzanne Beck, Joanne O'Brien, Simon Berrow, Ian O'Connor, and Dave Wall

Abstract As part of the European Union Marine Strategy Framework Directive (MSFD), member states are required to address noise pollution in the marine environment under Descriptor 11. This study aimed to provide a practical desk-based application of Descriptor 11 assessment, focusing on the main contributors of ocean noise pollution in Irish waters, seismic surveying and shipping. To highlight specific geographical areas subject to elevated levels of noise pollution, the proportion of days over a calendar year that seismic air guns were operational was calculated and the vessel density per 50-km^2 grids was determined across Ireland's exclusive economic zone (EEZ). Additionally, cetacean sighting data were used to determine the degree of spatial overlap between areas of elevated noise pollution and areas of cetacean abundance.

Keywords Marine Strategy Framework Directive • Impulsive • Continuous • Seismic • Shipping • Cetacean

1 Introduction

The underwater acoustic environment, once limited solely to inputs from geophysical and biological sound sources, now must adapt to increasing anthropogenic noise pollution. Seismic surveying is the primary technique used in the search for oil and

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natural gas reserves and is responsible for the emission of bursts of impulsive noise into the marine environment. Ireland was listed as one of the European Union (EU) countries with the highest energy dependence rates, 89% in 2011 (Eurostat 2013), resulting in an increased demand to discover indigenous natural gas and oil deposits. Seismic air guns generate predominantly low-frequency noise between 0 and 500 Hz and are one of the main sources of concern when assessing anthropogenic noise in Irish waters. Shipping has also long been recognized as the dominant source of underwater noise at frequencies below 300 Hz (Ross 1976; Hildebrand 2005), and increasingly, concerns have grown regarding continuous noise sources that propagate efficiently across ocean basins with the potential to cause further insidious impacts. In the north Pacific, low-frequency background noise has approximately doubled in each of the past four decades (Andrew et al. 2002), resulting in at least a 15- to 20-dB increase in ambient noise. Gerviase et al. (2012) also noted local rises in ambient-noise levels in the St. Lawrence Estuary, Canada.

The potential impacts of noise are not necessarily proportionate to the emitted noise levels. The assessment of the effects of noise must take into consideration the species of greatest concern, in terms of both spatial and temporal overlap but also in terms of vulnerability to increased noise emissions, conservation status of the population, and life history parameters. It is therefore important to utilize the existing knowledge on the distribution and ecology of sensitive marine species. There have been a number of recent reviews of the actual and potential impacts of sound sources on aquatic life (National Research Council 2003; Hastings and Popper 2005; Nowacek et al. 2007; Southall et al. 2007; Weilgart 2007; OSPAR 2009). Cetaceans have been continually highlighted as a high-risk group likely to suffer detrimental impacts from anthropogenic noise. This group has a highly developed auditory system and relies on sound as their primary sense for orientation, navigation, foraging, and communication (Au et al. 2000). The vocalizations and estimated hearing range of baleen whales overlap with the highest peaks of acoustic energy of air gun sounds and shipping and, consequently, these animals may be more affected by this type of disturbance than toothed whales (Southall et al. 2007). Twenty-four species of cetaceans have been recorded from Irish waters, six of which are baleen whales (O'Brien et al. 2009). *Balaenoptera physalus* (fin whale) is the most commonly observed large baleen whale in Irish waters. In 1991, Ireland declared its coastal waters a whale and dolphin sanctuary, but this was not supported by any additional legislative instruments. However, a number of national and international legislative agreements are in place for the protection of cetaceans, most notably the EU Habitats Directive. Additionally, translated into national law in 2010, the Marine Strategy Framework Directive (MSFD) aims to achieve good environmental status (GES) of European waters by 2020 and specifically addresses the impacts of noise in the marine environment. The ability to define and monitor GES under the MSFD remains a challenge, especially for Ireland, considering the scale of the Irish exclusive economic zone (EEZ) that occupies an area eight times that of the landmass. The primary objective of this study was to utilize the existing data to quantify the level of noise-emitting activities across specific geographic locations within Irish waters and determine the extent of spatial overlap with species of concern.

The mapping of these activities will allow the member states to outline areas of high noise pollution to aid in the decision as to where to locate long-term monitoring stations. Additionally, the data can be used in conjunction with direct measurements in the analysis of annual trends in ambient noise.

2 Methods

2.1 Analysis of Seismic Surveys

The MSFD Technical Subgroup on Underwater Noise made recommendations for the member states to create a noise register of licensed activities and through this establish the proportion of days within a calendar year over a specified area in which target sounds from seismic surveys occurred. To achieve this, the details of surveys conducted in waters under Irish jurisdiction from 2000 to 2011 were obtained from the Petroleum Affairs Division (PAD) of the Department of Communications, Energy and Natural Resources (DCENR). PAD divides the currently designated Irish continental shelf into quadrants of 1° latitude by 1° longitude and cell blocks of $10'$ latitude by $12'$ longitude, and this was deemed a suitable spatial scale for analysis of seismic activity under the MSFD Indicator 11.1.1. Noise emitted from the operation of air guns was considered the target sound, and "bang days" were then defined as days in which data from seismic surveying were acquired. Where acquisition dates were not available, seismic data acquisition was assumed for the entire survey duration. This is likely to be an overestimation of bang days, although instances of missing acquisition dates were minimal (7%). Noise maps were generated during the years 2000–2011 through ARCMap 10 geographic information system (GIS) software. If a survey spanned more than one cell block, then bang days were estimated as the total number of bang days divided by the total number of blocks for which the survey spanned. This is likely to be an underestimation of survey effort because most seismic surveys cover more than one cell block per day. Bang days across the entire study period were summed to create a noise map for 2000–2011 (Fig. 9.1). Surveys conducted from 2000 to 2011 in Irish waters were also categorized based on the volume of the air gun array in cubic inches and, where available, the peak-to-peak pressure in bar meters; where more than one survey covered a cell block, the mean volume/pressure was displayed.

2.2 Vessel Density

Details of vessel activity within Ireland's EEZ were acquired through automatic identification system (AIS) and vessel monitoring system (VMS) transponders. Data were obtained from the Irish Naval Service and the Department of Transport,

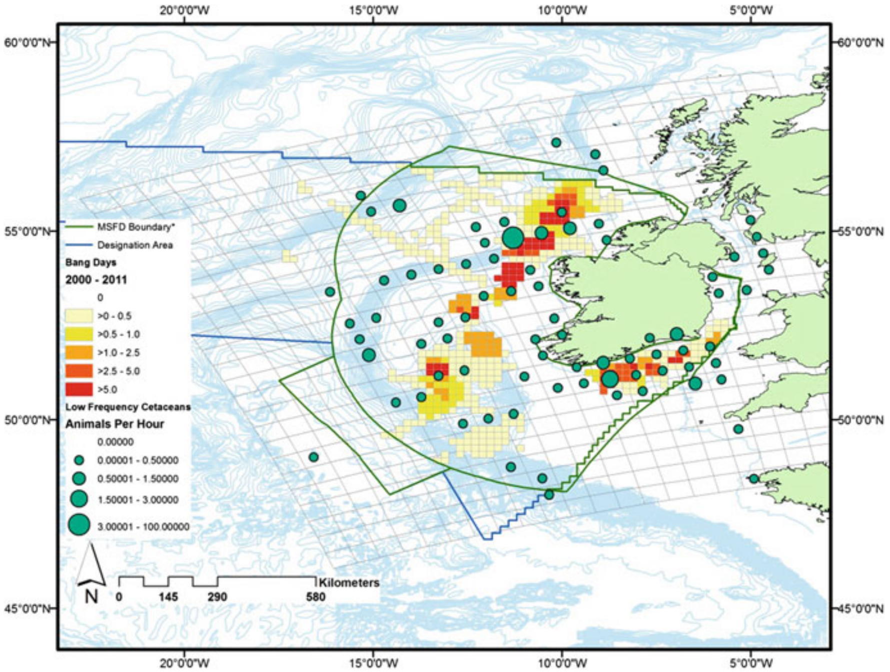

Fig. 9.1 Seismic survey pressure in waters under Irish jurisdiction between 2000 and 2011 with visual sightings of low-frequency cetaceans. Bang days, days involving acquisition of seismic data, are shown in a graduated color scheme, with darker colors representing the greatest number of bang days per cell. *MSFD* Marine Strategy Framework Directive

Tourism and Arts for Ireland. VMS data were obtained for 2010, 2011, and 2012, and AIS data were obtained for 2010 and 2011. VMStools, used under the R statistical software program, was used to format data-removing points on land, points recorded with implausible coordinates (i.e., latitudes >90° and longitudes >180°), points in harbors, and duplicates (records with the same coordinates and date-time stamps). Formatted data were then mapped using the ARCMap 10 GIS software as the total number of poll events across the European Environment Agency (EEA) 50-km^2 grid.

2.3 Cetacean Distribution

Visual cetacean sightings from 2005 to 2011 containing species identification, latitude, longitude, date, and time were obtained from the Irish Whale and Dolphin Group (Wall et al. 2013). Cetacean sightings were divided into the functional hearing groups previously categorized by Southall et al. (2007). Sightings databases were combined and formatted to remove any duplicate sightings and any sightings that could not be identified to a functional hearing group. Effort and sightings data were assigned to the EEA 50-km^2 grid using the ARCMap 10 GIS software. Total survey effort (hours surveyed in sea state 0–6) per 50 km^2 was summed and mapped for each grid square, as were the total number of individuals counted per 50 km^2 for each cetacean group recorded during the surveys. The relative abundance was calculated as the number of animals recorded per survey hour. Time-based analysis of the relative abundance was used because it was judged to be more suitable when amalgamating data from a variety of platforms with different speeds (Reid et al. 2003). The survey effort was graded based on sea state, with a sea state 2 or less for high-frequency cetaceans, sea state 4 or less for midfrequency cetaceans, and a sea state 6 or less for low-frequency cetaceans (Wall et al. 2013). Sea state grading is species specific, and so combining data into functional hearing groups has its limitations. The main concern is with the minke whale *Balaenoptera acutorostrata*, which is more elusive than the larger baleen whales and whose relative abundance will be understated when analyzed using sea states >3.

3 Results

3.1 Analysis of Seismic Surveys

Between the years 2000 and 2011, a total of 44 seismic surveys were conducted in waters under Irish jurisdiction. Of these, 25 surveys were two-dimensional (2-D) and 19 were three-dimensional (3-D). The duration of 2-D surveys during this time ranged from 1 to 51 days, with an average of 18 days. The duration of 3-D surveys ranged from 4 to 100 days, with an average of 31 days. For 2-D seismic exploration, an average of 5.77 cell blocks/day were surveyed. The more localized 3-D seismic surveys covered an average of 1.45 cell blocks/day. The most commonly used array volume in Irish waters between 2000 and 2011 was 3,000–4,000 in.^{3}. Trends in peak-to-peak (P-P) pressure were variable throughout the years; 2000 and 2008 reported the lowest values of 67 and 18 bar meters, respectively. The greatest P-P pressure was reported in 2011 with a value of 161.2 bar meters. Of the six surveys conducted in 2011, five of these used the same vessel and equipment setup.

3.2 Vessel Density

The AIS data-acquisition system was intermittently inactive for ~192 days in 2010 (53% of the year) and 241 days in 2011 (66% of the year) due to power failures and hardware malfunctions. The VMS data-acquisition system was fully functional throughout 2010, 2011, and 2012, and there were no reports of inactivity. Vessel density analyses in Ireland's EEZ have highlighted a number of areas that are

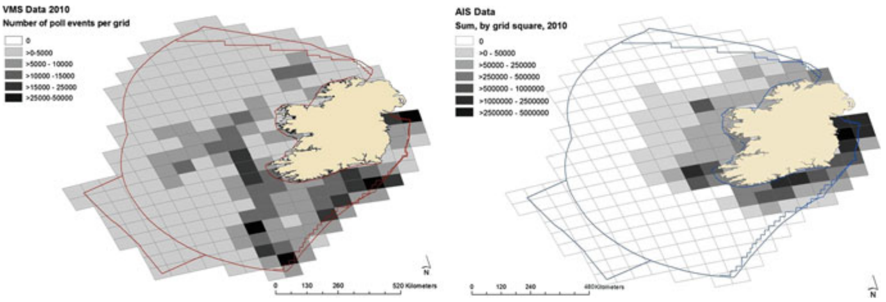

Fig. 9.2 Vessel density in 50-km^2 grids within Ireland's Exclusive Economic Zone from vessel monitoring system (VMS) data (*left*) and automatic identification system (AIS) data (*right*) for 2010

subject to higher densities of vessel traffic. AIS data analysis highlights the east and south coasts as high-density areas (Fig. 9.2); a proportion of this is likely to be attributed to passenger ferries operating routes between Ireland, the United Kingdom, and mainland Europe and commercial shipping on approaches to UK ports and the English Channel. VMS data analysis highlighted areas along the south coast of Ireland and areas further offshore south and southwest within Ireland's EEZ that were subject to high fishing vessel densities (Fig. 9.2). These areas were continually highlighted throughout 2010, 2011, and 2012.

3.3 Cetacean Distribution

The combined visual cetacean sightings database contained sightings from 2004 until 2011, with a total of 10,770 sightings. Of these, 2,466 sightings were identified as low-frequency cetaceans, 4,684 as midfrequency cetaceans, and 3,620 as high-frequency cetaceans. Results of cetacean distribution areas highlight a number of spatial overlaps with areas of noise-emitting activities in Irish waters. Quadrants 12, 18, 19, and 27 are of particular importance with high relative abundances of low-frequency cetaceans and high numbers of bang days for 2000–2011. Low-frequency cetaceans were also prevalent along the northwest continental shelf slope areas and slopes of the Porcupine Bank concurrent with high VMS densities. Low-frequency cetaceans also occurred along the south and southwest coasts of Ireland.

4 Discussion

The Irish Offshore Strategic Environmental Assessments (IOSEAs) 3 and 4, produced by PAD, estimate likely maximums of 49,000 km^2 for 2-D and 28,000 km^2 for 3-D surveys between 2010 and 2016 in the Rockall Basin alone (Petroleum

Affairs Division 2008, 2011). The operation of "open-door" licensing in the Irish and Celtic Seas estimated that a maximum of some 100,000 km^2 for 2-D and 30,000 km^2 for 3-D will be surveyed between 2011 and 2020, by which point Ireland hopes to achieve GES under the MSFD. This report has highlighted specific geographical areas with the greatest frequency of seismic exploration in terms of cumulative bang days per cell block. Noise emissions from 2-D surveys are spread across a wider area, leading to fewer bang days per survey block, for example, 0.17 bang days across 58 cell blocks for a 10-day survey, whereas noise emissions from 3-D surveys are usually focused on a smaller survey area, leading to a high number of bang days per survey block, for example, 0.22 bang days across 15 cell blocks for a 10-day survey. Studies have reported the importance of multiple pulses in comparison with single pulses (Southall et al. 2007). Additionally, previous work has documented responses that vary with air gun array volume. McCauley et al. (2000) reported avoidance by humpback whales at received levels of 160–170 dB re 1 μPa from a commercial array of 2,678 in.^{3} and from an experimental array of 20 in.^{3}, with avoidance from the commercial array at a distance three times greater than for the smaller volume experimental array. Harris et al. (2001) also reported a greater avoidance in seals during full-scale array usage as opposed to a single gun. The results presented here aim to develop an understanding of the varying intensities of air gun arrays used across Ireland's EEZ.

AIS and VMS data are useful resources for quantifying the densities of vessel traffic and allow member states to highlight "noisy" areas that may warrant further monitoring under the MSFD. Small recreational vessels and fishing vessels are also common in Irish waters but are not required to use AIS. The inclusion of VMS data aims to reduce this limitation. Vessel density analyses in Ireland's EEZ have highlighted a number of areas that are subject to higher densities of vessel traffic. The east and south coasts highlighted as high-density areas under the AIS analysis can likely be attributed to passenger ferries operating routes between Ireland, the United Kingdom, and mainland Europe and commercial shipping approaches to UK ports and the English Channel. VMS data analysis highlighted areas along the south coast of Ireland and areas further offshore south and southwest within Ireland's EEZ subject to high fishing vessel densities.

The cetacean distribution analysis highlights a number of spatial overlaps with areas of seismic surveying and vessel density in Irish waters. Of particular concern is the overlap with the low-frequency cetaceans because the auditory bandwidth of these species overlaps with the frequencies associated with shipping and seismic surveying. Quadrants 12, 18, 19, and 27 are of particular importance, with high relative abundances of low-frequency cetaceans and high numbers of bang days for 2000–2011. Low-frequency cetaceans were also prevalent along the northwest continental shelf slope areas and slopes of the Porcupine Bank concurrent with high VMS densities.

Low-frequency cetaceans also occurred along the south and southwest coasts of Ireland. The diet of fin and humpback whales in the Celtic Sea has been reported to be composed largely of *Clupea harengus* (herring) and *Sprattus sprattus* (sprat; Ryan et al. 2013). It is likely that the fishing vessels and the low-frequency cetaceans are utilizing the same natural resource in these areas of spatial overlap. Accurately predicting regions or periods where sensitive species are not present (or present in low densities) and authorizing surveying with this scientific knowledge in mind will help determine a spatial separation of surveys from periods of peak cetacean migration and foraging, minimizing exposure to anthropogenic noise and reducing the detrimental impacts of noise.

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Chapter 10

Is the Venice Lagoon Noisy? First Passive Listening Monitoring of the Venice Lagoon: Possible Effects on the Typical Fish Community

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Abstract Three passive listening surveys have been carried out in two of the three Venice lagoon tide inlets and inside the Venice island. The spectral content and the intensity level of the underwater noise as well as the presence or absence of *Sciaena umbra* and the distribution of its different sound patterns have been investigated in all the recording sites. The passive listening proved to be successful in detecting *S. umbra* drumming sounds in both Venice lagoon tide inlets. Our results indicate that the spectral content and the level of underwater noise pollution in the Venice lagoon could affect fish acoustic communication.

Keywords Noise • Brown meagre • Ship noise • Sound pressure level

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1 Introduction

The Venice lagoon is the largest Mediterranean lagoon, being a complex system connected to the Adriatic Sea through three tide inlets: Lido, Malamocco, and Chioggia. The lagoon is a complex mosaic of habitats comprising brackish water environments, sandbanks, shallow mudflats, barrier islands, lagoon islands, and a portion of the mainland with important rivers and broad agricultural areas. The lagoon hosts a well-structured fish community, functioning also as a nursery area for juveniles of many commercial species (Franco et al. 2006; Provincia di Venezia 2009; Franzoi et al. 2010). As a result, the Venice lagoon has been recognized as a Special Protection Area (IT3250046, 79/409/CEE, DGP n. 441/2007) and as a UNESCO World Heritage Site in 1987; furthermore, it comprises two Sites of Community Importance (IT3250030 “Laguna medio-inferiore di Venezia” and IT3250031 “Laguna superiore di Venezia,” 92/43/CEE, DPR 357/2003; Regione Veneto 2010). Despite this, the mainland harbor of Marghera in Venice is one of the widest and most complex industrial and shipping area in Europe (Regione Veneto 2010). The shipping traffic has been found to affect both the hydromorphology of the lagoon and the resuspension of sediments, strongly influencing natural erosion processes (Regione Veneto 2010). Although the presence of ship noise pollution could potentially interfere with important biological processes for fish survival and reproduction, the sea ambient-noise level in the Venice lagoon has never been investigated and so it is not regulated to date.

The aims of the present paper are to (1) monitor for the first time the spectral content and the intensity level of underwater noise in different locations of the Venice lagoon with the passive listening technique; (2) investigate the potential masking effect of the detected noise level on a fish target species; and (3) suggest the main contributors to the environmental noise level.

To achieve these goals, we used the passive-listening technique, a noninvasive, cheap, and reliable method for monitoring fish communicative sounds as well as anthropogenic noise levels (Rountree et al. 2006); this allowed the characterization of the noise acoustic energies (spectra, level, and duration) as potential factors injuring fish populations. In addition, this technique allowed the collection of data on the acoustic activity of the brown meagre (*Sciaena umbra* L., 1758), even in the context of the Venetian littoral zone (Picciulin et al. 2013). The brown meagre acoustic communication has been studied in detail (Codarin et al. 2009; Picciulin et al. 2012a, b, 2013) and this species is currently considered threatened in the Mediterranean Sea (Grau et al. 2009). For these reasons, the brown meagre has been chosen as a good target for addressing the potential effects of anthropogenic noise on fish.

2 Materials and Methods

On 5 August and 8 September 2011, two separate acoustic surveys were carried out (sea state <2 on the Douglas scale, wind speed <12 km/h). Out of 11 listening points, 10 were distributed across 2 of the 3 inlets connecting the Venice lagoon to the Adriatic Sea (the Lido and the Malamocco inlets); the remaining listening point was in the "Tegnua D'Ancona" (i.e., natural submarine rocky outcrops of biogenic concretions, irregularly scattered on the North Adriatic seabed). Furthermore, on 14 September 2010, another acoustic survey (for a total of four listening points) was carried out in the water channels inside the Venice island.

Recordings were obtained with a preamplified Reson TC4032 hydrophone (sensitivity 170 dB re 1 V/μPa, frequency range 5 Hz–120 kHz) connected to a portable microrecorder (Zoom H1) generating WAV files (sampling rate 44.1 kHz, 16 bit). For the recordings in the tide inlets, the hydrophone was dipped from a 7.5-m open boat to an average depth of 4 m (range 2–8 m, with a bottom depth across the listening points ranging from 4 to 20 m), while inside the Venice island, the hydrophone was dipped from the water channel's banks at approximately half of the bottom depth (range 0.5–1 m, with a bottom depth across the listening points ranging from 1 to 2 m).

Recordings (lasting 6–20 min) were analyzed minute by minute using Cool Edit Pro 2.0 software by audial and visual assessment of the spectrograms (sampling rate 44.1 kHz, 16 bit). The brown meagre sounds were aurally identified and subsequently classified into one of the three vocal patterns reported by Picciulin et al. (2012a); in addition, they were analyzed quantitatively by scoring the number of pulses per minute, here defined as pulse rate (PR). Instantaneous sound pressure level (SPL; L-weighted, 10 Hz–20 kHz, root-mean-square [rms] fast) was also measured per second along each acoustic sample using SPECTRA RTA software previously calibrated with a signal of 100 mV rms at 1 kHz (sensitivity 170 dB re 1 V/μPa); the equivalent continuous SPLs were further calculated by averaging the L-weighted SPL over the sample.

3 Results

The underwater noise level detected in the four listening points inside the Venice island ranged from 108 to 138 dB re 1 μPa (Fig. 10.1, Table 10.1). In particular, the spectral contents and the SPL of the noise produced by a passenger cruise ship passing ~250 m from the recording point "Bacino San Marco" is depicted in Fig. 10.1. These results are overlapped with the audiogram of the brown meagre (Codarin et al. 2009). The brown meagre produces sounds (knocks) with a main frequency of 166 Hz in April and of 262 Hz in July; its hearing thresholds are 90 dB re 1 μPa for sounds at 200 Hz and 82.2 dB re 1 μPa for sounds at 300 Hz (Codarin et al. 2009). Therefore, the noise emitted from a ship such a passenger cruise ship is 38 dB re 1 μPa higher than the brown meagre hearing threshold for the ship spectral content of 200 Hz and 54 dB re 1 μPa higher than the species hearing threshold for the ship spectral content of 300 Hz.

The mean SPL (from 40 Hz to 20 kHz) in the three recording areas (Lido and Malamocco tide inlets and the Venice island) ranged from 108 dB re 1 μPa to 137.6 dB re 1 μPa (Table 10.1). The mean SPL in the three recording areas is shown in Fig. 10.2 together with the sound production of the brown meagre (described in detail for each

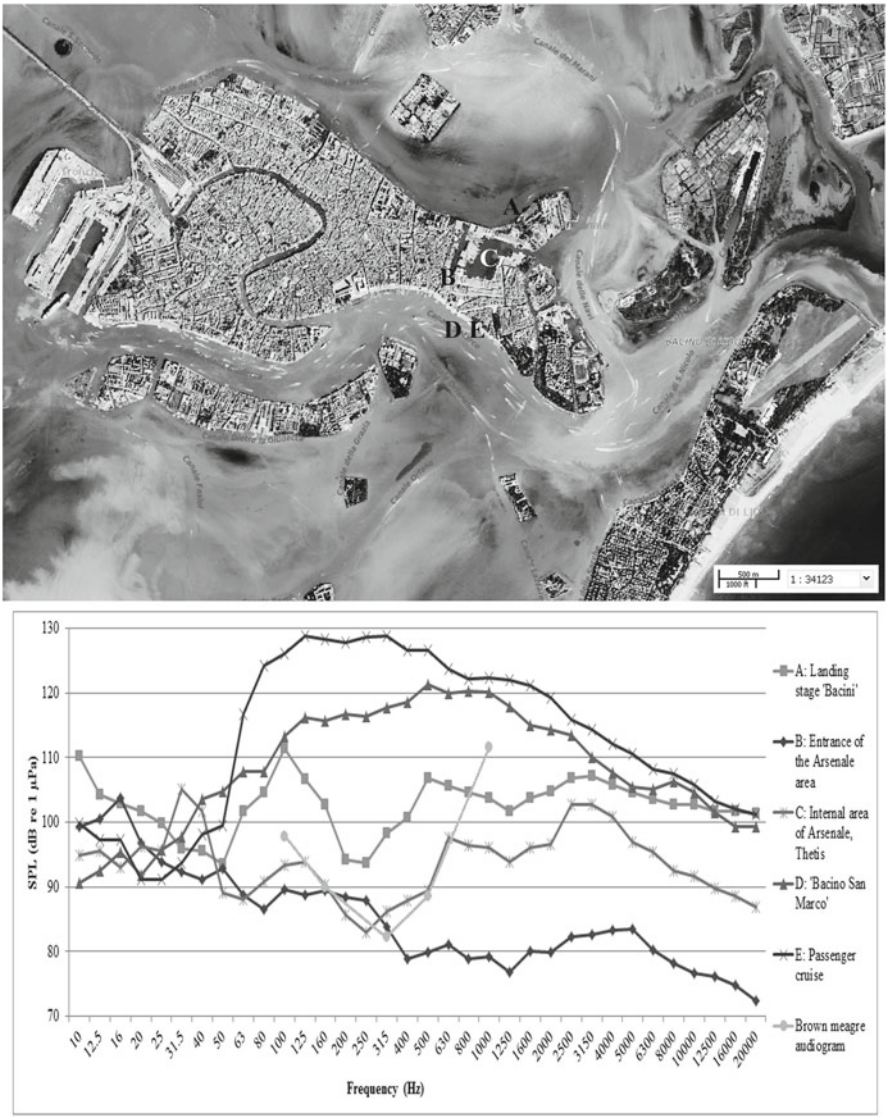

Fig. 10.1 *Top*: Map of the four listening points in the Venice island. *Bottom*: Noise spectral contents and sound pressure level (SPL) detected in the four listening points with the addition of the noise emitted by a passenger cruise transitting in the "Bacino San Marco." The audiogram of the brown meagre is overlapped

listening point in Picciulin et al. 2013) and the typology and the annual number of ships passages (Magistrato Acque 2007). The brown meagre produces sounds ranging from 119 to 129 dB re 1 µPa (Codarin et al. 2009), whereas the mean SPL detected in the Venice lagoon is 127 dB re 1 µPa. The detected noise level arises concerns about the possible masking effect on fish communicative sounds detection.

Table 10.1 Geographical coordinates, mean SPL, and brown meagre presence in each listening point

Recording area	Listening point	Geographic coordinates		*Sciaena umbra* presence	SPL (dB re 1 μPa)
		Latitude	Longitude		
Malamocco tide inlet	Lunata 1	45.32888	12.34416	Yes	128.3
	Lunata 2	45.32722	12.33972	Yes	137.6
	Lunata 3 esterno	45.32583	12.32750	Yes	133.4
	Soffolta 1	45.32166	12.32416	Yes	134.8
	Soffolta 2	45.31972	12.32305	Yes	137.6
	Soffolta 3	45.31722	12.32166	Yes	133.7
	Largo	45.32166	12.34083	Yes	132.2
Lido tide inlet	Tegnua d’Ancona	45.39916	12.55111	Yes	118.1
	Diga punta Sabbioni	45.42333	12.43722	No	115.4
	Diga San Nicolò	45.41861	12.42722	Yes	135.1
	Meda rossa	45.42666	12.41444	Yes	137.2
Venice island	Landing stage Bacini	45.43888	12.35722	No	119.7
	Entrance of the Arsenale area	45.43361	12.34972	No	108
	Internal area of Arsenale	45.4375	12.35333	No	112.1
	Bacino San Marco	45.43222	12.34944	No	129.8
	Bacino San Marco, passenger cruise	45.43222	12.34944	No	138

SPL sound pressure level

4 Discussion

Our results indicate that the Venice lagoon is a noisy place. This is not surprising considering that most of the traffic is here shipping based (public transports and merchant and passenger ships). Underwater noise was found to be more intense in the two tide inlets (with Malamocco being the noisiest one), whereas in the inner city, the highest SPL values were found in the Bacino San Marco where the ship traffic is more intense.

Different shipping pressures characterize the two tide inlets. Most ships transiting through the Lido inlet are passenger ships (86% of the total), and this type of marine traffic is strongly affected by seasonality, with the highest pressure during summer (Magistrato Acque 2007). This can affect the local fauna, with special regard to fish communities. Effects could range from nondetectable, sublethal behavioral changes to more dramatic physiological effects, including deafness or death (Wysocki et al. 2007; Ladich 2008). Although potential effects of anthropogenic noise depend on noise characteristics such as level, duration, and spectrum as well as on the hearing abilities of the fish species of interest (Wysocki et al. 2007), ship noise has been proven to elicit avoidance reactions in fishes, such as vertical

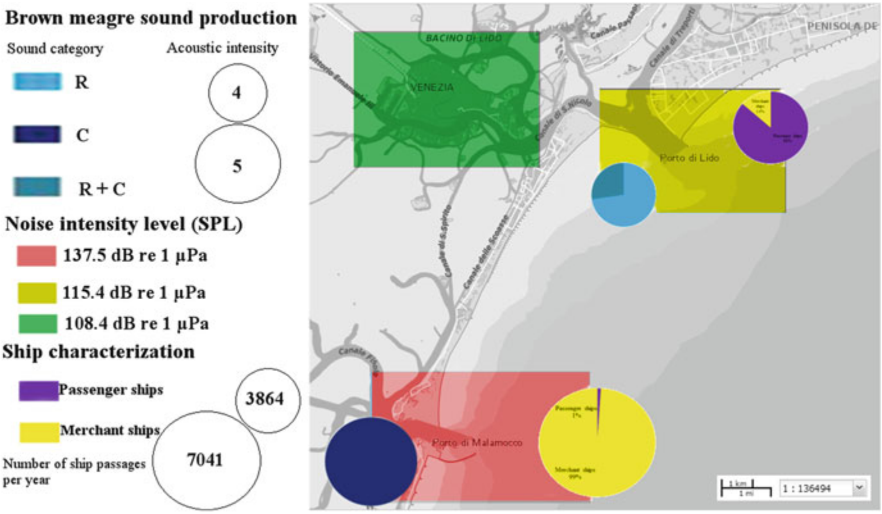

Fig. 10.2 Map of the Venice lagoon depicting each recording area (Malamocco and Lido inlets and Venice island). Background colors, noise intensity level; *blue* aerograms, *brown* meagre sound category and sound intensity (PR) scaled on an arbitrary quantitative scale from 0 (no sound) to 5 (maximum pulse rate, chorus) as described by Picciulin et al. (2013); *violet* and *yellow* aerograms, annual ship passages in the two tide inlets (Magistrato Acque 2007)

and horizontal displacement (Swierzowski 1999; Vabø et al. 2002; Handegard et al. 2003; Mitson and Knudsen 2003; Engås et al. 2011). Additionally, ship noise can elicit cortisol stress responses regardless of the fish hearing sensitivity range (Wysocki et al. 2006) or result in an increase of the cardiac output (Graham and Cooke 2008). Boat noise has been demonstrated to substantially reduce the brown meagre auditory sensitivity, and this masking effect is most pronounced in the frequency range where acoustic communication takes place (Codarin et al. 2009). Furthermore, in presence of continuous boat noise pollution, the brown meagre pulse rate has been proven to increase, possibly as a form of vocal compensation (Picciulin et al. 2012b).

The passive-listening technique proved to be successful in detecting underwater noise as well as *S. umbra* drumming sounds in two Venetian inlets, whereas this species was absent in the four listening points in the inner Venice lagoon. *Sciaena umbra* sounds have been detected in the Lido tide inlet (see Picciulin et al. 2013); here the highest levels of ship noise pollution are concentrated during this species breading season (May-August; Chauvet 1991). The brown meagre vocalizations are likely reproductive calls, serving for aggregating individuals and synchronizing spawning (Picciulin et al. 2012a); the level of noise pollution detected in the Lido inlet can therefore mask this species reproductive communication and ultimately affect its reproductive success. On the other side, *Sciaena umbra* chorus (i.e., almost continuous sound production; Picciulin et al. 2013) has been detected only in the Malamocco area, which is more from merchant ship traffic (99% of the total passages) and is not affected by seasonality (Magistrato Acque 2007). Considering that the annual number of ships transiting in Malamocco inlet is almost double the number of ships transiting in the Lido inlet (7,041 versus 3,864 passages in the Lido inlet in 2005; Magistrato Acque 2007), the concern about possible chronic effects on fish behavior, displacement, and communication is here of a certain importance.

Furthermore, in the Venice lagoon, the frequency range in which noise has most acoustic energy matches the hearing frequency range of most fish (Nedwell et al. 2004). Considering the single-noise source type, it has to be stressed that the passenger cruise ships, which usually enter the Venice lagoon through the Lido inlet to keep their route in the Bacino San Marco, emit noise in the frequency window that the brown meagre as well as many other fish species exploit for communication purposes (e.g., such noise is at least 30 dB higher of the brown meagre hearing sensitivity).

In conclusion, our results indicate a widespread underwater noise pollution in the Venice lagoon that could potentially affect local marine fauna. Picciulin et al. (2013) demonstrated that the fish community associated with *S. umbra* is ~40% commercially important species; therefore, the actual level of anthropogenic noise in the lagoon has potential effects not only on the biology of several fish species but also on the economic sector that depends on their availability, i.e., fishing.

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Chapter 11

Effect of Pile-Driving Sounds on the Survival of Larval Fish

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Abstract Concern exists about the potential effects of pile-driving sounds on fish, but evidence is limited, especially for fish larvae. A device was developed to expose larvae to accurately reproduced pile-driving sounds. Controlled exposure experiments were carried out to examine the lethal effects in common sole larvae. No significant effects were observed at zero-to-peak pressure levels up to 210 dB re 1 μPa^2 and cumulative sound exposure levels up to 206 dB re 1 μPa^{2}·s, which is well above the US interim criteria for nonauditory tissue damage in fish. Experiments are presently being carried out for European sea bass and herring larvae.

Keywords Offshore wind farms • Controlled exposure experiments

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1 Introduction

The rapid extension of offshore wind farms has led to an urgent need to acquire more knowledge on the potential ecological benefits and adverse effects of offshore wind farm construction and operation (Inger et al. 2009). Continuous sounds associated with operational wind farms and, in particular, loud impulse sounds associated with pile driving for the construction of wind farms may have adverse effects on marine mammals and fish.

Concern about the effects of pile-driving sounds on fish has led to the formulation of interim criteria for nonauditory tissue damage by the US Fisheries Hydroacoustic Working Group (FHWG; Oestman et al. 2009). However, knowledge of the sound levels at which mortality or injury will occur is limited for juvenile and adult fish and virtually nonexistent for fish eggs and larvae (e.g., Popper and Hastings 2009). While juvenile and adult fish may actively swim away from a sound source, planktonic larvae are passively transported by currents and therefore have limited capabilities of avoiding sound exposure. As a result, fish larvae may suffer more from underwater sound than older life stages.

In The Netherlands, permit applications for the construction of offshore wind farms are judged within the context of the European Natura 2000 network. Dutch Natura 2000 sites consist of shallow coastal and estuarine waters, which are important nursery grounds for many fish populations and important foraging areas for birds and mammals. For an impact assessment of Dutch offshore wind farms, the effect of pile-driving sound on the number of larvae that reach the inshore nursery areas was modeled (Prins et al. 2009). An existing egg and larval transport model (Bolle et al. 2009) was expanded, with the assumption that egg and larval mortality might occur in a 1-km radius around a pile-driving site. This effect range was presumed to be a worst-case scenario based on the limited information available at that time (e.g., the US FHWG criteria). The results indicated that offshore pile driving could cause an ecologically significant reduction in the number of fish larvae that reach the Natura 2000 sites. However, this conclusion depended entirely on the validity of the underlying assumption, yet little is known about the vulnerability of fish eggs and larvae to pile-driving sound.

The evident lack of knowledge on the effects of pile-driving sounds on fish larvae was acknowledged by the Dutch government, resulting in the current study. A device was developed in which loud impulse sounds, representative of pile-driving sounds, could be generated. This device was used to examine the effect of pile-driving sound on the survival of common sole (*Solea solea*) larvae in controlled exposure experiments (Bolle et al. 2012). Follow-up experiments are presently being carried out for European sea bass (*Dicentrarchus labrax*) larvae and will be undertaken for herring (*Clupea harengus*) larvae in the near future (Bolle, de Jong, Blom, Wessels, van Damme, and Winter, submitted manuscript).

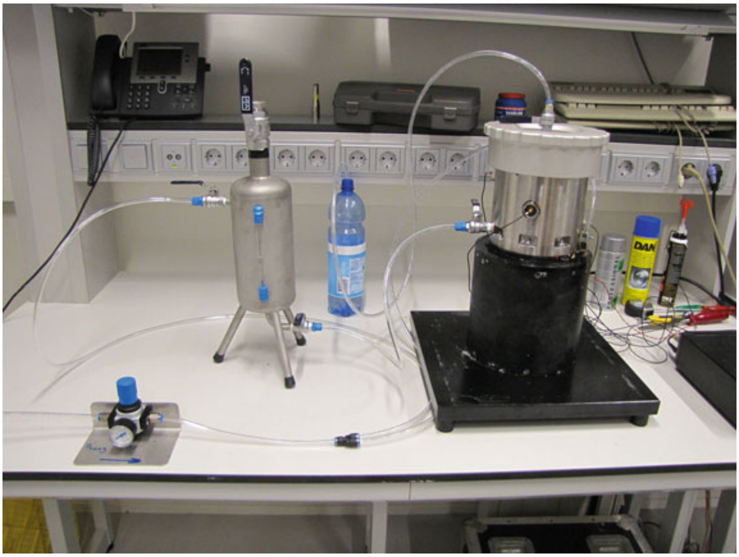

Fig. 11.1 The larvaebrator, a device developed to expose fish larvae to loud impulse sounds. See Bolle et al. (2012) for a schematic drawing of the larvaebrator

2 Materials and Methods

2.1 Larvaebrator

A device was developed to enable a controlled exposure of fish larvae to loud, low-frequency impulse sounds in a laboratory setting. This so-called larvaebrator was inspired by an existing laboratory setup for larger fish called the fishabrator or the high-intensity controlled-impedance fluid-filled wave tube (HICI-FT; Martin and Rogers 2008; Halvorsen et al. 2012a, b).

The larvaebrator consists of a rigid-walled cylindrical chamber driven by an electrodynamical sound projector (Fig. 11.1). Samples of up to 100 larvae can be exposed simultaneously to a homogeneously distributed sound pressure and particle velocity field at a controllable static pressure up to three bar. Sound pressure was measured by four transducers mounted in the wall of the chamber, and particle velocity was measured by an accelerometer mounted on the piston of the projector. Two configurations can be used: a pressure or a velocity excitation. Most experiments were carried using the pressure excitation configuration; the present paper is limited to these experiments. All experiments were done without static overpressure.

2.2 Pile-Driving Sounds

Because it is unclear which characteristics of pile-driving sound could cause mortality, the acoustic signals to which the fish larvae were exposed had to be representative of actual sound exposures in the field. This was achieved by playback of recorded pile-driving sound signals. The playback level is defined in terms of acoustic metrics that quantify the received signals (Ainslie 2011). As in most studies on the impacts of impulsive underwater sound on marine life, we chose to quantify sound in terms of sound exposure level (SEL; in dB re 1 $\mu Pa^2 \cdot s$), SEL per strike (SEL_{ss}), cumulative SEL(SEL_{cum}), and zero-to-peak sound pressure level ($SPL_{z\text{-}p}$; in dB re 1 μPa^2). Other metrics have sometimes been suggested for impulsive sounds (e.g., impulse, rise time, peak-to-peak sound pressure, kurtosis), but the associated dose–response relationships are even less clear than for SEL and $SPL_{z\text{-}p}$ (Popper and Hastings 2009).

Sound was recorded during a pile-driving event in the North Sea (OWEZ Wind Farm, 4-m-diameter steel monopole, water depth ±20 m, hammer strike energy ±800 kJ). The sound measured 100 m from the pile had a broadband $SPL_{z\text{-}p}$ up to 210 dB re 1 μPa^2 (zero-to-peak pressures up to 32 kPa) and a broadband SEL_{ss} up to 188 dB re 1 $\mu Pa^2 \cdot s$ (Ainslie et al. 2009). Playback levels for $SPL_{z\text{-}p}$ and SEL_{ss} were varied by scaling the pulse amplitude of the sound signal recorded 100 m from the pile. SEL_{cum} was varied by varying the number of strikes (strike rate = ~1 strike/s).

Typical recorded SEL_{ss} spectra (Ainslie et al. 2009) showed that the main (unweighted) energy of underwater pile-driving sound is generated in the 50-Hz–1-kHz bands. The playback sound was limited to this frequency band to avoid excitation of spurious resonances in the larvaebrator. Measurements showed that the projector reproduced the original recorded signal shape accurately and that the main characteristics of the frequency spectrum were reproduced to an acceptable level (Bolle et al. 2012).

2.3 Fish Larvae

Common sole and European sea bass larvae were obtained from commercial hatcheries. Fertilized eggs were purchased and reared to the required larval stage in the laboratory. Because herring cannot be obtained from a commercial hatchery, eggs and sperm were collected from ripe herring adults caught during the annual herring larvae survey. The eggs were fertilized in vitro onboard the vessel and reared to the required larval stage in the laboratory.

For common sole, three larval stages, 1, 2, and 3-4a (according to the classification by Al-Maghazachi and Gibson 1984), were used in the experiments. For European sea bass, two larval ages were used: 18–19 days after hatching (DAH) and 38–39 DAH. For herring, we intend to use two larval ages. The common sole does not have a swim bladder in the adult life phase; a swim bladder is developed during the larval phase but disappears during metamorphosis. Inflated swim bladders are clearly visible in most larvae in stage 3-4a. Initial swim bladder inflation is achieved by the passage of gas from the digestive tract to the swim bladder, but there are indications that further inflation may be realized by secretion of the gas gland (Boulhic and Gabaudan 1992). Herring has a physostomous swim bladder throughout its life (Blaxter and Batty 1984). The swim bladder of European sea bass is physostomous in the early larval stages and physoclistous in the late larval to adult stages (e.g., Chatain 1986).

2.4 Experimental Design

Each experiment consisted of a treatment (control or exposure) followed by a monitoring period. For each experiment, ±25 (common sole) or ±30 (European sea bass) larvae were taken from the cultivation chamber and subjected to treatment. After treatment, each batch of larvae was transferred to a separate container and held during the monitoring period. The control groups underwent the same handling procedures as the exposure groups. The response variable that was measured was mortality; the numbers of dead and live larvae in each batch were counted directly after the treatment and daily during a monitoring period of 7–10 days. The batch containers were coded and except for the observations directly after the treatments, the person scoring mortality was not aware of the treatment belonging to the code. The treatments within each replication round were applied in random sequence to avoid bias due to potential serial effects.

For both the common sole and European sea bass, a pilot series of experiments was carried out with a relatively low number of replicates (2–5) per treatment. The results of these pilot series were used in a statistical power analysis to determine the number of replicates required in the final series of experiments. The final series for the common sole consisted of 3 treatments for each of the 3 larval stages, with 15 replicates/treatment; the final series for European sea bass consisted of 4 treatments for each of 2 larval ages, with 10 replicates/treatment. The treatments applied in the final series are listed in Table 11.1.

The experiments were performed in accordance with Dutch law concerning animal welfare. Each series of experiments was approved by the Animal Ethical Commission (DEC) of Wageningen UR.

2.5 Statistical Analysis

Estimates of mortality and the significance of differences between exposure and control groups were calculated using a generalized linear mixed model. This model treats the data (death or survival of a larva) as outcomes of binomial trials in which the probability of death is a function of treatment and takes into account the possible

Table 11.1 Treatments by larval stage and larval age in the final series of experiments

	$SPL_{z\text{-}p}$ (dB re 1 µPa^2)	SEL_{ss} (dB re 1 µPa^2·s)	SEL_{cum} (dB re 1 µPa^2·s)	Number of strikes
Common sole larval stage 1				
Treatment 1	0	0	0	0
Treatment 2	205	181	201	100
Treatment 3	210	186	206	100
Common sole larval stage 2				
Treatment 1	0	0	0	0
Treatment 2	205	180	200	100
Treatment 3	209	185	205	100
Common sole larval stage 3-4				
Treatment 1	0	0	0	0
Treatment 2	205	181	201	100
Treatment 3	209	185	205	100
European sea bass 18–19 DAH				
Treatment 1	0	0	0	0
Treatment 2	210	187	207	100
Treatment 3	210	187	217	1,000
European sea bass 38–39 DAH				
Treatment 1	0	0	0	0
Treatment 2	210	187	207	100
Treatment 3	210	187	217	1,000

Sound metrics are measured (common sole) or imposed (European sea bass) zero-to-peak sound pressure level ($SPL_{z\text{-}p}$), single-strike sound exposure level (SEL_{ss}), and cumulative sound exposure level (SEL_{cum}). *DAH* days after hatching

random variation in mortality between batches (termed "batch effect" hereafter). It is necessary to account for such batch effects because, if present, the assumption (under the binomial distribution) that the outcomes of larvae are determined independently of one another is violated. The statistical model was formulated as follows. (1) The logit-transformed probabilities of death (P_{ij}; in treatment i and batch j) were modeled as a function of treatment and random batch effect (α_j): $\text{logit}(P_{ij}) = \text{treatment}_i + \alpha_j$. (2) The number of dead larvae in batch j from treatment i (k_{ij}) were assumed to be binomially distributed depending on the probability of death (P_{ij}) and the number of larvae at the beginning of the experiment (N_{ij}): $k_{ij} \sim \text{Bin}(P_{ij}, N_{ij})$. (3) The random batch effects (α_j) were assumed to be normally distributed with mean zero and variance σ^2: $\alpha_j \sim N(0, \sigma^2)$. The model was fitted separately to the data for each larval stage and for a specified monitoring period. The model was fitted and significance tests were performed using the glimmix procedure in SAS (SAS/STAT software, SAS Institute, Inc., Cary, NC).

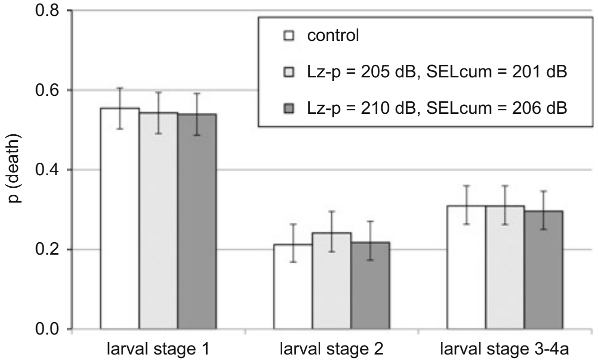

Fig. 11.2 Estimated mean probability (*P*) ± 95% confidence intervals of death 7 days after treatment for each larval stage and each treatment. $L_{z\text{-}p}$ zero-to-peak sound pressure level, SEL_{cum} cumulative exposure level. Modified from Bolle et al. (2012)

3 Results

Results for European sea bass and herring are not yet available (Bolle, de Jong, Blom, Wessels, van Damme, and Winter, submitted manuscript); the results presented in this paper are limited to the common sole (Bolle et al. 2012). In the pilot series, no immediate effect of sound exposure was observed. For stage 2 larvae, mortality at the end of the monitoring period was lower in the control group than in the highest sound exposure group, but this difference was not significant, possibly due to low statistical power. No indications for an effect were observed in the other larval stages. High variability between batches with the same treatment was observed.

In the final series, no immediate effects nor clear differences between exposure and control groups at the end of the monitoring period (Fig. 11.2) were observed. The factor treatment was insignificant for all larval stages. Standard errors on the mortality estimates were such that an exposure effect >14% could be excluded at the 95% confidence level (Bolle et al. 2012).

4 Discussion

Common sole larvae were exposed to pile-driving sound levels up to $\text{SEL}_{\text{cum}} = 206$ dB re 1 $\mu\text{Pa}^2\cdot\text{s}$, which is much higher than the interim criterion defined by the US FHWG for nonauditory tissue damage in small fish (183 dB re 1 $\mu\text{Pa}^2\cdot\text{s}$), but no significant effects on survival were observed. No previous studies have addressed the effect of pile-driving sound on fish larvae. A few studies have investigated the effect of pile-driving sound on juvenile fish and a few studies have investigated the effect of other low-frequency, loud impulse sounds on fish larvae (Table 11.2).

Table 11.2 Overview of the studies to date that examined the effects of low-frequency impulse sounds on larval or juvenile fish

Study	Species	Life stage	Sound source	$SPL_{z\text{-}p}$ (dB re 1 µPa^2)	SEL_{ss} (dB re 1 µPa^2·s)	SEL_{cum} (dB re 1 µPa^2·s)	Effect
Booman et al. (1996)	Cod, saithe, herring, turbot, plaice	Eggs and larvae	Seismic air guns	220–242			Injuries and lethal effects in some species/stages
Govoni et al. (2008)	Spot, pinfish	Late larvae	Explosion	234	182		Lethal effects
Bolle et al. (2012)	Common sole	Larvae	Pile driving	210	186	206	No lethal effects
Halvorsen et al. (2012b)	Chinook salmon	Juveniles	Pile driving	204	177	210	Onset injury
Casper et al. (2012)	Chinook salmon	Juveniles	Pile driving		187	217	Recoveries from injuries
Halvorsen et al. (2012a)	Lake sturgeon, Nile tilapia	Juveniles	Pile driving		177	207	Onset injuries
Halvorsen et al. (2012a)	Hogchoker	Juveniles	Pile driving		186	216	No injuries
Bolle, de Jong, Blom, Wessels, van Damme, and Winter, submitted manuscript	Sea bass, herring	Larvae	Pile driving	210	189	217	Results not yet available

The sound metrics are the levels at which effects were observed or the maximum levels were recorded if no effects were observed

The limited results available to date provide a first indication that injuries or mortality in fish larvae and juveniles may not occur at SEL_{cum} values below 207 dB re 1 μPa^2·s and $SPL_{z\text{-}p}$ values below 204 dB re 1 μPa^2 (Table 11.2). Further work on other species is required before these findings can be extrapolated to fish (larvae) in general. Moreover, the research to date has mainly focused on injury and mortality assessments, whereas sound exposure may also affect physiology or behavior and hence predation and starvation risks.

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Chapter 12
Challenge of Using Passive Acoustic Monitoring in High-Energy Environments: UK Tidal Environments and Other Case Studies

Cormac G. Booth

Abstract The use of passive acoustic monitoring (PAM) around marine developments is commonplace. A buffer-based PAM system (e.g., C-POD) is a cost-effective method for assessing cetacean acoustic presence. Devices have been deployed by Sea Mammal Research Unit (SMRU) Marine around the United Kingdom, allowing an examination of the performance of C-PODs with respect to background noise, tilt angle, and environmental factors. C-PODs were found to often only monitor for a few seconds of each minute, resulting in significant loss of monitoring time. Issues were likely driven by environmental and deployment factors. The practical limitations of buffer-based PAM systems in high-energy/noisy environments are indicated here.

Keywords Impact monitoring • Noisy environments • Marine mammals • Limitations • Passive acoustic monitoring

1 Introduction

An important component of the environmental impact assessment process for commercial developments is understanding the marine mammal species present and, if possible, the details of any spatial and temporal variations present around the site. Typically, cetacean surveys have used visual methods to detect animals, but small cetaceans such as harbor porpoises and other delphinids can be extremely difficult to observe in the wild because they spend the majority of their time underwater, generally occur in small groups, and often present a low profile at the surface.

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Passive acoustic monitoring (PAM) is the term used to describe the process of passively listening for sounds emitted by animals. This is a widely used tool that allows the collection of long-time series datasets for vocal species and, if properly implemented, does not interfere with the animals' behavior (Zimmer 2011). Harbor porpoise sighting rates are heavily impacted by poor sea conditions, with rates dropping precipitously beyond sea state 2 (Hammond et al. 2002). Beyond sea state 4, it becomes very difficult to observe many other cetaceans. Porpoises, in particular, are much easier to detect acoustically because they regularly produce sounds for orientation, navigation, foraging, and communication. Therefore, using PAM techniques, information on the presence of porpoises can be gathered during periods when visual observation is not possible (e.g., in high sea states, in darkness, during periods of low visibility).

A commonly used PAM tool is the C-POD (and its predecessor the T-POD; Chelonia 2013). These devices are specifically designed to detect and process the vocalizations of high-frequency cetaceans such as harbor porpoises and midfrequency cetaceans such as delphinids. They also log information during deployment, including water temperature, C-POD angle (from vertical), and the number of click sounds logged by the C-POD in each monitoring minute. The use of C-PODs has become widespread; however, many studies fail to take into account the performance of units and, specifically, how often the units monitor in assessing and interpreting the patterns of cetacean detections made using C-PODs.

Here, detection data using C-PODs from a range of sites were initially collected to assess the presence of harbor porpoises around proposed marine development sites including tidal energy, offshore proposed wind, and civil engineering sites. Detailed modeling analyses allowed an assessment of the performance of C-PODs as a PAM tool in collecting porpoise presence data.

2 Methods

C-PODs were deployed across a range of sites to acoustically detect the presence of harbor porpoises to determine the occurrence of the species in these regions along with any spatial and/or temporal variations in presence. Data were collected between 2010 and 2013 from sites around the United Kingdom and the coastal Northeast Atlantic.

C-PODs are self-contained submersible ultrasound monitoring units that include a hydrophone element, filters, processors, battery pack, and memory. These units passively detect the vocalizations produced by cetacean species in the frequency range between 20 and 170 kHz. The units register the start time of vocalization (with a 5-μs resolution) along with the frequency, intensity, click bandwidth, and envelope. The basic metric they generate is the detection positive minute (DPM), which is defined as any minute in which a porpoise click train is detected. In analyses, this metric is often scaled up to more coarse temporal units (e.g., DPM/10 min;

DPM/h; or a binary variable, detection positive hour, which is an hour containing one or more DPMs). C-PODs (and T-PODs) have been used in a number of studies to assess the distribution of harbor porpoises in the context of monitoring marine renewable energy developments and interactions with static fishing nets and "pingers," which are acoustic devices used to reduce harbor porpoise bycatch (e.g., Carlström et al. 2009; Todd et al. 2009; Brandt et al. 2011; Dähne et al. 2013).

C-PODs log continuously 24 h/day and are therefore useful for providing continuous data on porpoise and dolphin acoustic activity within the detection radius of the unit. However, it is important to clarify the extent of their utility. (1) They provide data on porpoise and dolphin activity (absence/presence) in a given geographical area (i.e., within a certain range of the hydrophone). (2) They can be used to compare the relative frequency of occurrence/echolocation activity between sites or through time. (3) They will only record porpoises and dolphins that are actively echolocating. (4) They cannot be used for estimating the abundance of harbor porpoises/dolphins on their own. Harbor porpoises produce echolocation clicks relatively consistently (Akamatsu et al. 2007); these clicks are highly directional and high frequency in nature (Verboom and Kastelein 1997). This means that C-PODs can detect the vocalizations produced by porpoises out to ~200–300 m from the unit and if the porpoises are pointing their head in the direction of the C-POD.

C-PODs were deployed on moorings comprising a U-shaped configuration with two anchor points. The C-PODs were fixed to the riser between 2.5 and 5 m from the seabed, and during the servicing and maintenance visits of the units, only one end of the mooring was retrieved and a new C-POD was deployed. The C-POD mooring was designed to keep the unit sitting upright in the water column.

Initial data processing was performed using C-POD.exe (versions 2.036–2.041), which allows visual analysis of all logged clicks and an assessment of how these clicks have been classified into different click trains (using the KERNO classifier from C-POD.exe version 2.0 and newer). The C-POD software package will automatically classify any click trains into one of five categories, reflecting how likely the train is to be a porpoise or dolphin click train. These are high quality (Hi), moderate quality (Mod), low quality (Lo), unknown (?), and all quality (all Q). This allows the user to check for an incorrect assignment of click trains. Only Hi and Mod quality detections have been used in the following analyses. The use of the two highest quality click-train classes may mean that occasional true click trains that are detected by the C-PODs have been rejected, but it minimizes the inclusion of false positive detections in data analysis, which was the priority in assessing cetacean activity.

When configuring C-PODs before deployment, it is possible to set the maximum number of clicks to be logged (described as Nall) in any given minute of monitoring. Selecting this measure is a trade-off between maximizing the amount of monitoring time in each minute (it is possible for the ClickMax to be reached in <1 min in noisy environments) against running out of storage space before the C-PODs are retrieved (and losing valuable monitoring time). Here the default value of 4,096

Table 12.1 Candidate covariates in each model

Candidate covariate	Description
%TimeLost	Percentage of time lost due to the C-POD unit reaching the maximum in each monitoring minute
C-POD angle	Tilt angle of the C-PODs
Month	Month of the year
DayNightIndex	Position in day/night (0/2 = sunrise, 0.5 = middle of day, 1 = sunset, 1.5 = middle of night)
Position in lunar cycle	Position in the spring-neap tidal cycle (0/1 = spring tides, 0.5 = neap tides)
Position in daily tidal cycle	Position in the daily tidal cycle (0/1 = low water, 0.5 = high water)
Water temperature	Water temperature (°C) logged by T-PODs and C-PODs

clicks/min was selected as the limit. Along with the details of porpoise detections, the C-POD.exe software provides a measure of %TimeLost (described as "the percentage of time in periods when the POD had maxed out; Chelonia 2013). Here the %TimeLost was used as a covariate to assess whether porpoises were avoiding periods or areas of high noise and/or the detection of porpoise click trains was impacted by periods of high noise. Values ranged between 0 and 100%, where 100% would indicate that no data were collected and 0% indicates that the C-POD unit was monitoring for the entire minute.

2.1 Data Analysis

The C-POD outputs were summarized into hour-long listening intervals in which porpoises were detected. The response variable used in the modeling was a binary value indicating whether one or more porpoise DPMs occurred in the DPH (1) or not (0). The response was modeled with respect to a range of covariates (multicollinearity between covariates was assessed to avoid poor model selection; Table 12.1) inside a generalized additive model (GAM) with logit link and binomial errors. Generalized estimating equations (GEEs) were used to govern model selection because they account for autocorrelation that exists in the C-POD datasets and because observations were collected close together in time and space. This method is becoming well-established in cetacean distribution modeling (over standard GAM/generalized linear model [GLM] approaches), and the methods described by Booth et al. (2013) were followed. GEEs have also been used to investigate cetacean occurrence from autocorrelated data (Panigada et al. 2008; Pirotta et al. 2011; Bailey et al. 2013). Here all statistical analyses were conducted using the computer package "R" (R Core Development Team 2006; available at http://www.r-project.org/).

3 Results

Each of the site-specific harbor porpoise models constructed after model selection included the %TimeLost covariate. In many of the models, this covariate was the most important factor in explaining the patterns that generated the data. Tidal, diel, and other survey covariates (e.g., which C-POD unit was deployed and the angle of the C-POD from the vertical) were also included relatively consistently in the final models for each site. The relationship between %TimeLost and porpoise detections is shown in Fig. 12.1. As the percentage of monitoring time that was lost due to the buffer filling up increased (i.e., monitoring time decreased), the number of porpoise detections decreased. This pattern was consistent across the different study sites and indicates that it is a consistent issue in the use of C-PODs in a region with any tidal movement.

Porpoise detection rates decreased significantly as the time lost through noise increased. This pattern could be explained by porpoises avoiding the region during "noisy" periods. It is also possible that the ClickMax buffer being reached in each monitoring minute was indicative of the detection of porpoises being affected during the noisiest periods. This was the most important variable in explaining the variation in detections.

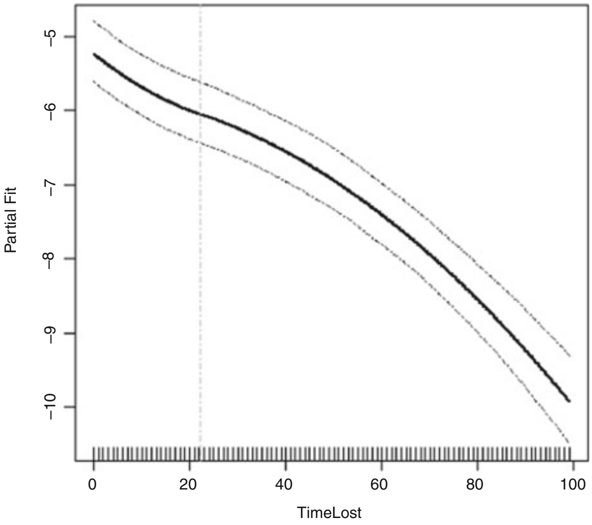

Fig. 12.1 Partial residuals plot showing the relationship between porpoise detections and the percentage of time lost (TimeLost) of each monitoring unit. Partial fit explains how porpoise acoustic activity changes as the TimeLost increases. *Dotted lines* above and below the *black line* indicate the 95% confidence intervals for the predicted relationships (i.e., it is highly likely that the "true" relationship fits between the *upper* and *lower dotted lines*). The *vertical dashed line* indicates the knot location in the model

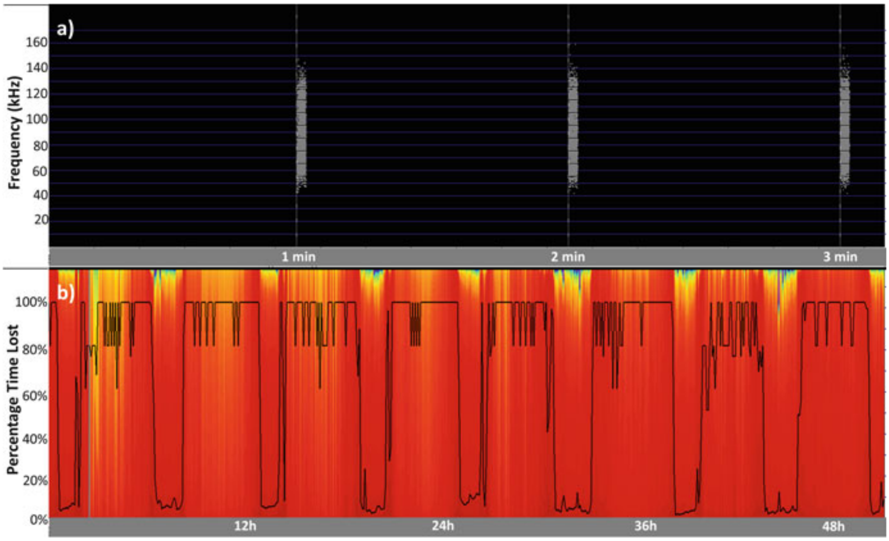

Fig. 12.2 (**a**): Close-up plot of three successive minute of monitoring. *Vertical dotted lines* indicate the divisions between monitoring minutes. *Black panel* shows all the clicks (*small white dots*) logged in each minute by frequency. In each minute period, only a few seconds of actual "listening" occurs before the ClickMax buffer is reached and the unit becomes dormant before waiting for the next available monitoring minute period. This pattern is repeated in noisy periods. (**b**): A long-term plot showing 2 days of C-POD data with respect to the "Nall" level (expressed as Percentage Time Lost). *Red* indicates high-intensity noise and *blue* indicates low-intensity noise. Monitoring period is dominated by high-intensity noise. *Black line* shows the number of clicks logged in each minute relative to the maximum. The "plateauing" occurs when the buffer is reached within a minute or less. It is clear due to the extensive plateauing in these data that the buffer is frequently reached, meaning that there is little actual effort in "listening" for dolphins or porpoises in each minute

3.1 Effect of Noisy Environments

The performance of PAM equipment can be impacted by noisy environments. In the case of PODs, they work by monitoring each minute with a predetermined "buffer," previously described as the Nall setting. In each minute, the POD will continue to monitor until this maximum buffer is reached. From assessing the raw data, it is clear that the C-PODs deployed suffered from some data loss due to the buffer being reached consistently (Fig. 12.2). In the worst periods, the buffer was reached within ~3 s (Fig. 12.2a), meaning that the unit would lie dormant for 57 s before starting up again and that this pattern repeated itself. At a coarser scale (Fig. 12.2b), it appears that significant monitoring time is still lost. The cyclical nature of this pattern suggests that it may be linked to tidal flows. However, this was not captured in the assessments of collinearity as part of the modeling process.

4 Discussion

In each of the individual site-specific models in which harbor porpoise detections (made using C-PODs) were analyzed, the %TimeLost covariate had significant influence. As noise levels increased, porpoise activity decreased (often dramatically), suggesting that either ambient-noise conditions impacted the ability for porpoises to be detected using the C-PODs (i.e., high noise causing the POD to reach its click maximum before the minute of monitoring was completed) or the animals were avoiding noisy areas or periods. It is important to note that this issue was not limited to regions of high tidal activity. Some of the sites were of moderate tidal range and this issue was still apparent and limiting in the data.

The inclusion of this covariate is an effort to "control for" any issues caused by noise and should be considered when using C-PODs without "correcting" for this bias, which may lead to incorrect interpretations of patterns in the data. This is a particularly important issue to be addressed in the context of monitoring as part of environmental impact assessments (EIAs) or postconsent monitoring where the quantification of potential impacts must be robustly approached. This issue should also be considered carefully in projects using T-PODs where it is not possible to record the time lost.

The setting used in calculating the %TimeLost for C-POD deployments was the default of 4,096. This can be set higher, allowing more flexibility in monitoring. Any future deployments should consider setting this to a higher level and deploying for shorter periods (because by setting a higher buffer level, the memory gets filled up quicker with more clicks, necessitating the need for more frequent service visits). In addition, it may be possible to reduce the issues encountered here through the development of specialized moorings to minimize exposure of the drivers of this issue. Alternatively, there are a number of other PAM systems that could be used; many of these systems don't have a buffer and so should not be limited in the way C-PODs appear to be.

The issues raised here should be considered when designing a static PAM survey and/or when analyzing and interpreting data collected using buffer-based PAM systems such as C-PODs.

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Chapter 13

Hearing Mechanisms and Noise Metrics Related to Auditory Masking in Bottlenose Dolphins (*Tursiops truncatus*)

Brian K. Branstetter, Kimberly L. Bakhtiari, Jennifer S. Trickey, and James J. Finneran

Abstract Odontocete cetaceans are acoustic specialists that depend on sound to hunt, forage, navigate, detect predators, and communicate. Auditory masking from natural and anthropogenic sound sources may adversely affect these fitness-related capabilities. The ability to detect a tone in a broad range of natural, anthropogenic, and synthesized noise was tested with bottlenose dolphins using a psychophysical, band-widening procedure. Diverging masking patterns were found for noise bandwidths greater than the width of an auditory filter. Despite different noise types having equal-pressure spectral-density levels (95 dB re 1 μPa^2/Hz), masked detection threshold differences were as large as 22 dB. Consecutive experiments indicated that noise types with increased levels of amplitude modulation resulted in comodulation masking release due to within-channel and across-channel auditory mechanisms. The degree to which noise types were comodulated (comodulation index) was assessed by calculating the magnitude-squared coherence between the temporal envelope from an auditory filter centered on the signal and temporal envelopes from flanking filters. Statistical models indicate that masked thresholds in a variety of noise types, at a variety of levels, can be explained with metrics related to

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the comodulation index in addition to the pressure spectral-density level of noise. This study suggests that predicting auditory masking from ocean noise sources depends on both spectral and temporal properties of the noise.

Keywords Signal • Detection • Comodulation

1 Introduction

Cetaceans are acoustic specialists that rely heavily on sound for communication, navigation, hunting, foraging, and protection (Mann et al. 2000). Individual fitness can be compromised if ocean noise has a negative impact on these basic survival abilities. When one sound interferes with the ability to detect, discriminate, or recognize another sound, auditory masking occurs.

1.1 Critical Ratios and Critical Bands

Early studies focused on measuring critical bands (CBs) and critical ratios (CRs) and how the spectral density of noise within a limited bandwidth (e.g., one-third octave) affected masked thresholds. CRs have become a standard metric for describing and predicting auditory masking due to their relative simplicity. CRs can be calculated by

$$\mathrm{CR} = \mathrm{L_S} \quad \mathrm{L_N} \tag{13.1}$$

where $\mathrm{L_S}$ is the signal sound pressure level (SPL) at threshold (in dB re 1 μPa) and $\mathrm{L_N}$ is the spectral density of the noise (in dB re 1 $\mu\mathrm{Pa}^2/\mathrm{Hz}$). The accuracy of CRs in predicting masked tonal thresholds in environmental noise is limited, however, primarily because CRs assume that the noise is Gaussian (G) and that masking is limited to a narrow band of noise centered on a signal's frequency (Au and Moore 1990). In non-G noise, CRs have been shown to vary by as much as 22 dB (Fig. 13.1).

1.2 Comodulation Masking Release

In addition to the spectrum level of noise, the time-domain features of noise also affect auditory masking. When noise is amplitude modulated (AM) across frequency regions (i.e., comodulated), a release from masking known as the comodulation masking release (CMR) occurs. Several studies have demonstrated CMR in odontocetes using synthetic noise and natural noise sources (Branstetter and

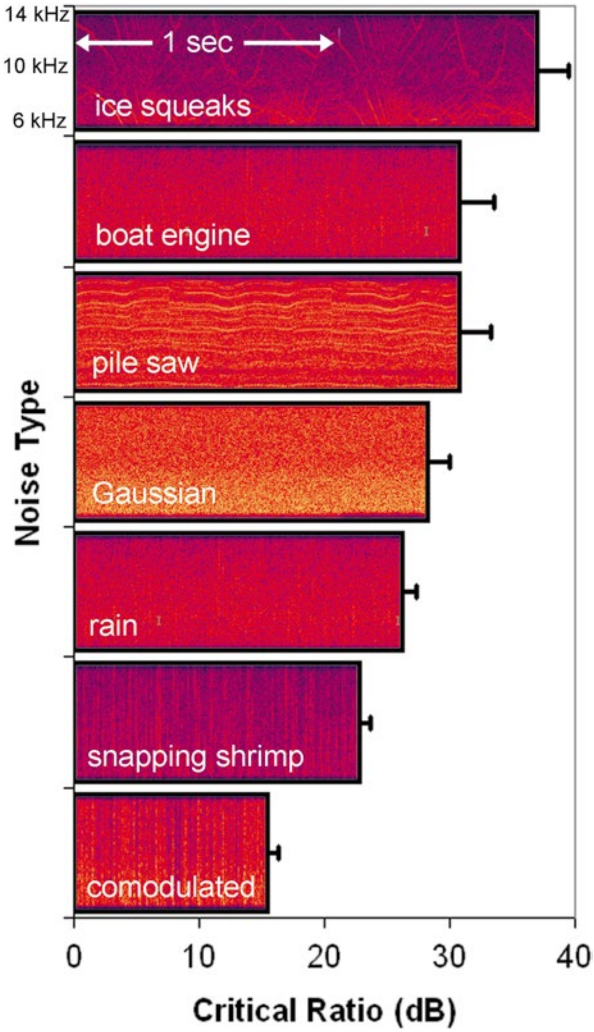

Fig. 13.1 Critical ratios (+SD) and spectrograms for seven different noise types. The bandwidth of each spectrogram is 6–14 kHz. Data are from Branstetter et al. (2013)

Finneran 2008; Erbe 2008; Trickey et al. 2011; Branstetter et al. 2013). Lower AM rates result in a more salient CMR (Branstetter and Finneran 2008). Amplitude modulation must be coherent across auditory filters (Branstetter et al. 2013); thus, noise bandwidths must exceed a critical band for CMR to occur. As a result, time-domain noise metrics in addition to the pressure spectral density (PSD) are needed to describe and predict auditory masking from different noise types.

1.3 Study Goals

Experiments were conducted to quantify the relationship between specific noise metrics and masked-detection thresholds. Several noise types (biological, anthropogenic, and synthesized noise) at four different spectral-density levels (85, 90, 95, and 100 dB re 1 μPa^2/Hz) were used to measure masked-detection thresholds for a 10-kHz tonal signal. Statistical models were then used to identify the noise metrics related to auditory masking.

2 Participants

Three Atlantic bottlenose dolphins (*Tursiops truncatus*) participated. All participants had normal hearing at the frequencies tested. The study followed a protocol approved by the Institutional Animal Care and Use Committee of the Biosciences Division, Space and Naval Warfare Systems Center Pacific and all applicable US Department of Defense guidelines for the care of laboratory animals.

2.1 Behavioral Hearing Tests

Participants were trained to position on an underwater bite plate and whistle in response to a 10-kHz tone (tone trial) or remain silent if no tone was present (catch trial). A one-down one-up adaptive-staircase procedure (Levitt 1971) was used to estimate thresholds at the 50% correct level. Noise was continuously played (from the same projector as the signal) for the duration of the threshold estimation procedure. A complete description of the testing procedure can be found in Branstetter et al. (2013).

Seven noise types were used as maskers (Fig. 13.1). Five of the noise types were field recordings: snapping shrimp, rain, boat, pile saw, and ice squeaks. The remaining two noise types, G and comodulated noise, were synthesized (see Branstetter and Finneran 2008). All noise types were band-pass filtered (6–14 kHz) to produce a flat spectrum. Noise level was an independent variable and varied from 80 to 100 dB re 1 μPa^2/Hz in 5-dB increments. Complete details of the noise recordings and synthesis can be found in Branstetter et al. (2013).

2.2 Noise Metrics

The noise metrics used can be divided into three categories, (1) waveform, (2) frequency spectrum, and (3) the envelope of the temporal waveform, and are listed in Table 13.1.

Table 13.1 Metrics and abbreviations used in the statistical models

Waveform		Spectrum		Temporal envelope	
P	Peak pressure	PSD	Pressure spectral-density level	ESD	Envelope standard deviation
PP	Peak-to-peak pressure			EKURT	Envelope kurtosis
rms	Root-mean-square pressure			CI	Comodulation index
SEL	Sound exposure level				
KURT	Kurtosis				

These metrics were used as explanatory variables in the multiple-regression models

An additional metric, the comodulation index (CI), was designed to measure the degree to which a noise sample is comodulated (i.e., amplitude modulation is correlated across frequency regions). To calculate the CI, noise is first band-pass filtered into a signal (S) band (9.5–10.5 kHz), a low-frequency (LF) band (8.5–9.5 kHz), and a high-frequency (HF) band (10.5–11.5 kHz). The bandwidth of the filters approximates the auditory filter bandwidth at these frequencies (Branstetter and Finneran 2008). The Hilbert envelope is extracted from the output of each filter and the DC component is subtracted. The magnitude-squared coherence (MSC) is then calculated between the S and LF envelopes and again between the S and HF envelopes, resulting in two 1-dimensional (1-D) arrays (Fig. 13.2). To reduce MSC values from the two 1-D arrays to a single value (CI), the maximum MSC value was selected from both arrays, resulting in the CI (Fig. 13.2).

2.3 Statistical Models

Multiple-regression models were constructed in the statistical language R Development Core Team (2012). Noise metrics (Table 13.1) were modeled as explanatory variables to evaluate their relationship to the resulting masked thresholds. Models were simplified by fitting a maximum model and then removing the nonsignificant explanatory variables (stepwise deletion).

3 Results

An exponential decay function including both PSD and CI proved to be the most parsimonious, best fit model

$$y = b_1 PSD + b_2 e^{-CI/b_3} \tag{13.2}$$

where y is the predicted threshold, and b_1, b_2, and b_3 are parameter estimates. Figure 13.3 displays masked threshold values fit with the exponential decay model

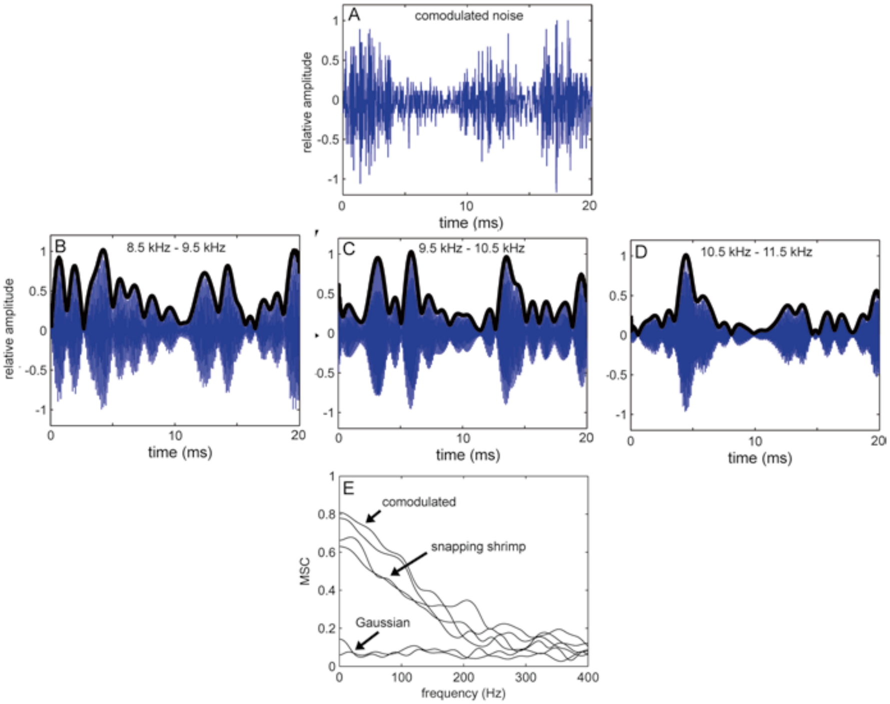

Fig. 13.2 Processing stages to calculate the comodulation index (CI). (**a**) Noise is band-pass filtered into a signal (S) band, a low-frequency (LF) band, and a high-frequency (HF) band (waveforms in **b**, **c**, and **d**, respectively). The Hilbert envelope is extracted from each band of noise (*thick lines* in **b**, **c**, and **d**, respectively). The magnitude-squared coherence (MSC) is calculated between the Hilbert envelopes from the S and LF bands and again from the S and HF bands. (**e**) MSC as a function of frequency for three noise types. Each function is the average of five 100-ms segments. Each noise type has two functions because the S band is compared with both the LF and HF bands. Noise that is comodulated has a higher MSC at the lower frequencies. The CI was calculated by selecting the largest MSC for a given noise type regardless of frequency

in which $b_1=1.13$, $b_2=32.84$, and $b_3=0.24$. Data are displayed with a surface plot representing model predictions. The data points represent masked thresholds from 3 participants, with 12 different noise types collected over 6 year. Analysis of the residual errors demonstrates that the two-parameter model produces much better fits than CR predictions while still being simple and parsimonious

4 Discussion

A simple two-parameter model including both the PSD and CI appears to explain the bulk of the auditory-masked threshold data within this study. The relationship between thresholds and PSD is linear, whereas the relationship between thresholds

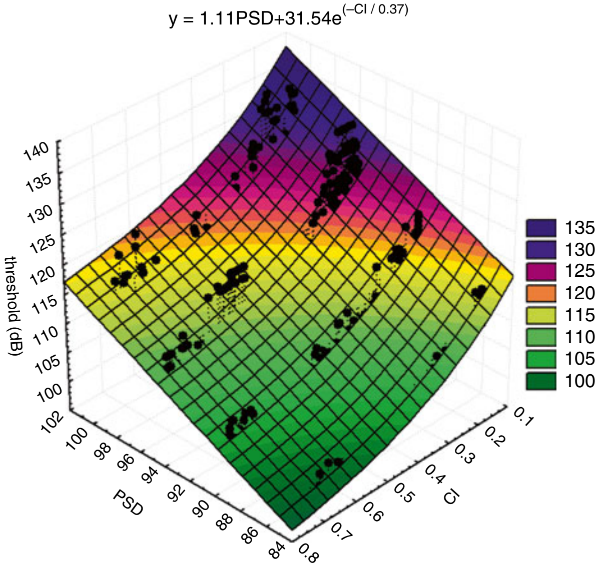

Fig. 13.3 Model fits (surface plot) and masked thresholds (data points). *PSD* pressure spectral density

and CI appears to follow a decelerating trajectory. Mitigating the effects of auditory masking depends on our ability to describe and predict masking in a wide range of conditions. Predictions based on CRs (or other spectra–based measurements) are an important first step, but the predictions are limited to the noise type in which the CRs were estimated (i.e., G noise). Time-domain metrics related to noise must be included to improve masked-threshold predictions.

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Chapter 14
Effects of Hatchery Rearing on the Structure and Function of Salmonid Mechanosensory Systems

Andrew D. Brown, Joseph A. Sisneros, Tyler Jurasin, and Allison B. Coffin

Abstract This paper reviews recent studies on the effects of hatchery rearing on the auditory and lateral line systems of salmonid fishes. Major conclusions are that (1) hatchery-reared juveniles exhibit abnormal lateral line morphology (relative to wild-origin conspecifics), suggesting that the hatchery environment affects lateral line structure, perhaps due to differences in the hydrodynamic conditions of hatcheries versus natural rearing environments, and (2) hatchery-reared salmonids have a high proportion of abnormal otoliths, a condition associated with reduced auditory sensitivity and suggestive of inner ear dysfunction.

Keywords Lateral line • Neuromast • Inner ear • Hair cell • Otolith

1 Introduction

Natural aquatic environments feature a host of biotic and abiotic sound sources that give rise to a highly complex acoustic scene (Popper 2003). Fish and other aquatic vertebrates have evolved a variety of specialized faculties for the encoding of and

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reaction to biologically important acoustic and hydrodynamic signals, with an impressive heterogeneity of mechanosensory mechanisms across species and environments (e.g., for Weberian ossicles and canal neuromasts, see Webb et al. 2008; for swim bladder-lateral line [laterophysic] connections, see Webb et al. 2006). Studies employing experimental manipulation of the rearing environment in both aquatic (three-spine stickleback *Gasterosteus aculeatus*, Wark and Peichel 2010) and nonaquatic (rat, Chang and Merzenich 2003) vertebrates have established that the morphology of mechanosensory systems (i.e., the auditory and lateral line systems) depends in part on the mechanosensory stimuli experienced during ontogeny.

We recently became interested in the potential effects of highly unnatural hatchery rearing environments on the ontogeny of mechanosensory systems in Salmonidae, a family of teleost fish with complex life histories traversing diverse marine and freshwater environments. Among other salmonids, Pacific (*Oncorhynchus* sp.) and Atlantic (*Salmo salar*) salmon are of particular interest to fishery biologists and ecologists because anthropogenic activities have led to widespread declines in natural populations. To mitigate such declines while sustaining salmon fisheries, federal, state, and private organizations have undertaken large-scale hatchery rearing of juvenile salmon (see Araki et al. 2008). Unfortunately, once released into the wild (typically at the age of ~3 months to 1 year), hatchery-reared juveniles survive at low rates compared to wild-origin juveniles (e.g., Raymond 1988), such that hatcheries have proven much less effective than initially hoped, both economically and ecologically (Araki et al. 2008). Recognizing that the mechanosensory environment of typical hatcheries is drastically different from the natural environments in which wild-origin juveniles develop, we hypothesized that hatchery-reared salmonids might exhibit mechanosensory abnormalities relative to wild-origin juveniles. Here we describe recent findings from several studies on the lateral line and auditory systems in *Oncorhynchus*.

2 Effects of Hatchery Rearing on the Lateral Line

Wild-origin juvenile steelhead (anadromous *Oncorhynchus mykiss*, “sea-run rainbow trout”) generally mature in turbulent freestone rivers or creeks composed of pools, riffles, and cascades that were created by in-stream flow obstructions and geomorphological features. In contrast, hatchery-origin juvenile steelhead are typically reared in raceways, barren, uniform-depth cement tanks flushed by low-velocity unidirectional flow-through systems (e.g., Kihslinger and Nevitt 2006). The hydrodynamic environment of hatchery-reared juveniles is therefore drastically different (and much less dynamic) than that experienced by wild-origin juveniles. Although this disparity has been recognized by other investigators and linked to reduced swimming endurance (Chittenden et al. 2010) and brain size (Kihslinger and Nevitt 2006) in raceway-reared fish, the effects of the rearing environment on the lateral line system, the system that encodes hydrodynamic information, had never (to our knowledge) been assessed.

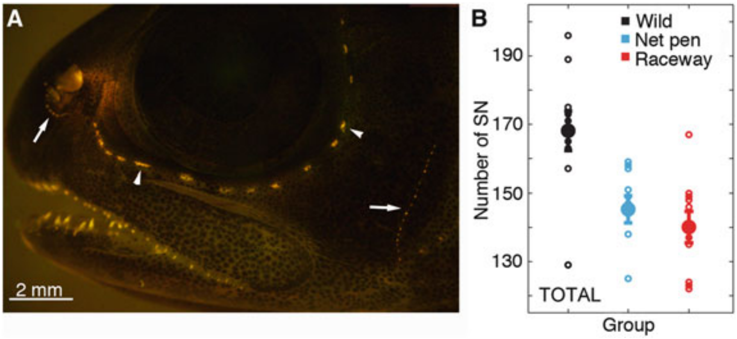

Fig. 14.1 (**a**) Lateral line morphology of a wild-origin juvenile *Onchorhynchus mykiss* in a fish labeled with the fluorescent vital dye DASPEI. *Arrows*, examples of clusters (stitches) of superficial neuromasts; *arrowheads*, examples of canal neuromasts. (**b**) Total number of superficial neuromasts (SN; summed across the left and right sides) per fish (*open circles*) and per group (*solid circles*). Values are mean thresholds ± SE. There were significant differences in neuromast number between groups (1-way ANOVA, *P* = 0.001). Significant differences were also observed across individual regions of interest/stitches (data not shown). Modified from Brown et al. (2013) under the Creative Commons License (CC BY 3.0)

In *O. mykiss* as in other teleost fishes, the lateral line system consists of distributed clusters of mechanoreceptive hair cells known as neuromasts rooted either on the skin or scales ("superficial neuromasts" [SNs]) or in subcutaneous canals ("canal neuromasts" [CNs]). SNs are generally sensitive to low-frequency or DC signals (e.g., currents), whereas CNs are sensitive to higher frequency pressure gradients (for a review, see Webb et al. 2008). In *O. mykiss* and other *Oncorhynchus*, SNs and CNs contribute to rheotaxis (flow orientation), station holding in currents, prey capture, and spawning behaviors (Satou et al. 1994; Montgomery et al. 1997, 2002). Because these behaviors are critical to survival and are also known to be impaired in hatchery-origin salmon (e.g., Chittenden et al. 2010), we reasoned that the lateral line systems of hatchery-origin juveniles might exhibit differences from those of wild-origin juveniles. As a first step, we analyzed the lateral line morphology in juvenile *O. mykiss* from a natural free-flowing stream (wild-origin controls) and from two different hatcheries where fish were reared in either (1) typical concrete raceways or (2) floating net pens suspended on a natural lake. All fish were collected from the same region in western Washington State and were genetically similar, although not identical (Washington Department of Fish and Wildlife 2002; Brown et al. 2013). Using fluorescent-labeling methods, we observed that hatchery-reared juveniles from both hatcheries possessed significantly fewer SNs (in total and within defined regions of interest) than wild-origin conspecifics (see Fig. 14.1).

Although it is tempting to relate the observed differences in neuromast number to hydrodynamic environmental differences (cf. Wark and Peichel 2010), most notably, the low-velocity uniform flow in the hatchery environment versus the turbulent and dynamic flow in the natural stream environment, the differences could be attributable to other factors. High rearing densities in hatcheries, for example, precipitate repeated negative physical interactions between fish, resulting in fin deformations and diffuse tissue damage (Kindschi and Barrows 2009; Chittenden et al. 2010), the latter of which could manifest as physical SN ablation. This explanation seems unlikely to us because damaged SNs were only rarely observed and sensory hair cell number within SNs did not differ across groups (Brown et al. 2013). A genetic origin of the differences also seems unlikely given the conservation of the lateral line system across *Oncorhynchus* sp. and the specific similarity of the stocks we studied (Washington Department of Fish and Wildlife 2002), although we cannot exclude this possibility without replicating the study using juveniles of common parentage.

Although we are not aware of other studies that have examined lateral line morphology in hatchery versus wild-origin salmonids, a few studies have noted abnormal lateral line structure in other hatchery-reared fishes. Ellis et al. (1997) reported differences in canal morphology between hatchery-reared and wild turbot (*Scophthalmus maximus*), with hatchery fish having longer canals with greater branching. Carrillo et al. (2001) found a reduction in trunk canal length and altered canal morphology in hatchery-reared gilthead sea bream (*Sparus aurata*) compared with wild conspecifics. However, neither of these studies quantified neuromast or hair cell number and both used indirect measures of lateral line morphology (e.g., canal pores; Carrillo et al. 2001), making it difficult to directly compare results. Nonetheless, the existing data collectively suggest that hatchery rearing alters lateral line morphology. Physiological and behavioral studies are required to establish the functional consequences of these morphological changes.

3 Effects of Noise Exposure in the Hatchery

Pumps and aerators used to maintain water quality in hatcheries can produce high levels of ambient noise. Sound pressure levels (SPLs; re 1 μPa root-mean-square [rms]) range from < 100 dB in earthen ponds with no running mechanical systems to 110–120 dB in typical concrete raceways to 130 dB in fiberglass tanks (Bart et al. 2001; Davidson et al. 2007). The bulk of this noise is low frequency and falls squarely within the range of sensitivity of the auditory and lateral line systems of salmonid species, including *O. mykiss* (Wysocki et al. 2007) and *O. tshawytscha* (chinook salmon; Oxman et al. 2007).

3.1 Effects on Hearing

A few recent studies have examined the effects of hatchery noise exposure on fishes, although only a subset of these have assessed auditory function. Wysocki et al. (2007) found that 8 months of exposure to a 150 dB broadband stimulus, meant to emulate hatchery noise conditions, had no effect on auditory evoked potential (AEP) thresholds in juvenile *O. mykiss* compared with conspecifics raised in relatively quiet conditions (115 dB). Salmon are hearing generalists, meaning that they lack swim bladder-inner ear coupling or other accessory structures that enhance auditory sensitivity (Popper and Lu 2000). Goldfish (*Carassius auratus*) and other otophysan fishes, which possess a swim bladder-inner ear connection and are thus termed "hearing specialists," show significant temporary threshold shifts after 24 h of exposure to 140 dB white noise (Smith et al. 2004). Based on the linear threshold shift hypothesis proposed by Smith et al. (2004), low-frequency sounds of 175 dB or greater would be required to cause a significant threshold shift in salmonids. Although some anthropogenic sound sources such as pile driving or low-frequency sonar greatly exceed this SPL (Popper et al. 2007; Halvorsen et al. 2012), hatchery conditions do not, making it unlikely that chronic exposure to hatchery noise would directly affect salmonid auditory function.

3.2 Hatchery Noise and Stress

Chronic exposure to hatchery noise could, however, indirectly affect auditory function. Two studies examined the influence of noise exposure on stress and growth in *O. mykiss*. Wysocki et al. (2007) found that fish raised in different sound-intensity treatments did not differ significantly in growth rate or response to stressors as measured by plasma chloride and glucose levels and by pathogen challenge. Similarly, 5 months of exposure to elevated noise (149 dB) did not alter the growth or survival of juvenile *O. mykiss* (Davidson et al. 2009). However, diminished growth was detected in fish from the 149 dB treatment when measured at an earlier time point in the study (after 1 month of noise exposure), suggesting that chronic noise might be an initial stressor to which the fish acclimate over time.

One putative manifestation of hatchery stress, whether due to noise conditions or other factors (e.g., crowding, handling stress), is aberrant otolith formation. Otoliths, or ear stones, are calcium carbonate structures that overlay the sensory epithelia in the three end organs of the fish inner ear (saccule, utricle, and lagena; Popper and Lu 2000). In most fishes, including salmonids, the saccule is the primary auditory end organ and the associated sagitta (saccular otolith) is composed of the aragonite form of calcium carbonate (Campana 1999; Popper and Lu 2000). Accretion of the less stable calcium carbonate polymorph vaterite has been reported in the sagittae of many hatchery fishes, particularly salmonids (e.g., Sweeting et al. 2004; Oxman et al. 2007; Chittenden et al. 2010; Brown et al. 2013). Vaterite-containing sagittae are correlated with elevated AEP thresholds in juvenile *O. tshawytscha*, with fish possessing vaterite sagittae in both saccules exhibiting significantly higher thresholds than fish with two aragonite sagittae and fish with one sagitta of each type possessing an intermediate threshold shift (Oxman et al. 2007; Fig. 14.2). This reduction in sensitivity likely occurs because the reduced density of the vaterite causes improper movement of the otolith in the sound field, reducing the stimulation to the associated sensory hair cells (Oxman et al. 2007).

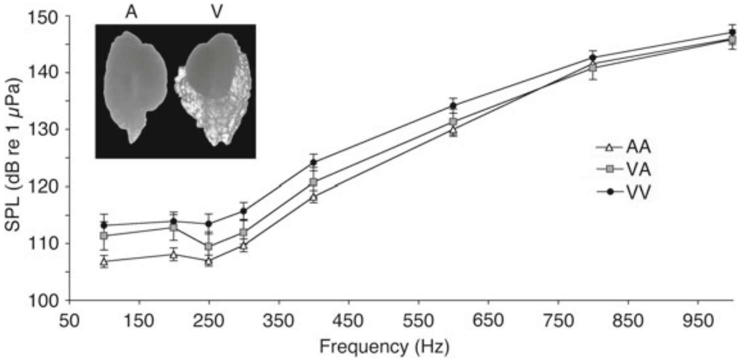

Fig. 14.2 Audiograms of juvenile *O. tshawytscha* with two aragonite sagittae (saccular otoliths; AA), one vaterite and one aragonite sagitta (VA), and two vaterite sagittae (VV). Significant threshold shifts were recorded in fish possessing at least one vaterite sagitta (ANOVA, $P<0.01$) compared with fish with two normal (aragonite) sagittae. *SPL* sound pressure level. Values are mean thresholds ± SE. Inset, aragonite (A) and vaterite (V) sagittae removed from a single animal and viewed with transmitted light. Modified from Oxman et al. (2007) and reproduced with permission

The causes of vaterite deposition are unknown, with "hatchery stress" being a vague and unsatisfying explanation (e.g., Sweeting et al. 2004; Oxman et al. 2007). At a systemic level, in ovo thyroid hormone manipulation has been reported to alter the relative frequency of aragonite versus vaterite sagittae in *O. mykiss*, suggesting that circulating hormone levels, perhaps in response to hatchery stress, can influence otolith formation (Coffin et al. 2012). Limited evidence suggests that the survival rates for steelhead with vaterite sagittae may be lower than those for fish with normal aragonite otoliths (Veinott and Porter 2013). Therefore, hatchery conditions may have an adverse affect on the hearing capabilities, and possibly the overall fitness, of hatchery-reared salmonids by inducing aberrant otolith formation.

4 Future Directions

The studies described suggest a number of additional experiments. Studies of the lateral line should be repeated using salmonids from common parentage raised under precisely controlled hydrodynamic conditions and evaluated at multiple developmental time points. Functional studies are also indicated to specify the physiological consequences of altered lateral line morphology; these data should be supplemented with behavioral data (e.g., using a lateral line-mediated prey-tracking task; cf. Montgomery et al. 2002). In the domain of hearing, additional studies of auditory function (e.g., auditory nerve recordings) may further specify impairments associated with otolith aberrations. Collectively, these experiments would offer substantial data on normal and impaired salmonid mechanosensory function that could point to specific modifications of hatchery-rearing practices that might, in turn, improve juvenile survival rates and augment the long-term efficacy of hatchery programs.

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Chapter 15
Effects of Impulsive Pile-Driving Exposure on Fishes

Brandon M. Casper, Thomas J. Carlson, Michele B. Halvorsen, and Arthur N. Popper

Abstract Six species of fishes were tested under aquatic far-field, plane-wave acoustic conditions to answer several key questions regarding the effects of exposure to impulsive pile driving. The issues addressed included which sound levels lead to the onset of barotrauma injuries, how these levels differ between fishes with different types of swim bladders, the recovery from barotrauma injuries, and the potential effects exposure might have on the auditory system. The results demonstrate that the current interim criteria for pile-driving sound exposures are 20 dB or more below the actual sound levels that result in the onset of physiological effects on fishes.

Keywords High-intensity controlled-impedance fluid-filled wave tube • Barotrauma • Ear • Swim bladder • Anthropogenic sound • Nonauditory tissues

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1 Introduction

There is considerable concern about the potential effects of impulsive pile driving on fishes. However, very little is known about such effects because much of the earlier work was done under field conditions where it was impossible for investigators to have any control over the stimulus because the sounds from pile driving were generated during actual construction operations (reviewed by Popper and Hastings 2009). More recently, however, studies conducted in the laboratory using devices that simulate aquatic far-field, plane-wave acoustic conditions of actual pile-driving signals provide insights into the effects where there is excellent control of the sound field (e.g., Bolle et al. 2012; Halvorsen et al. 2011, 2012a, b; Casper et al. 2013a, b; Popper et al. 2013). This paper reviews the work done in our laboratory utilizing the high-intensity controlled-impedance fluid-filled wave tube (HICI-FT), a device that enabled examination of the pile-driving effects on five species of fishes.

1.1 The Regulatory Issue

Current interim regulations on the sound levels to which fishes may be exposed from pile-driving activities were developed in 2008 (Woodbury and Stadler 2008; Stadler and Woodbury 2009). These regulations focused on developing criteria for sound exposures that could produce the onset of physiological injury. Although carefully noted as being interim and conservative, these regulatory levels are being applied throughout the West Coast by the National Marine Fisheries Service (NMFS), and they have been applied at other locations around the world. The interim criteria developed by the Fisheries Hydroacoustics Working Group (FHWG) were a peak sound pressure level ($\mathrm{SPL_{peak}}$) of 206 dB re 1 µPa and a cumulative sound exposure level ($\mathrm{SEL_{cum}}$) of 187 dB re 1 $\mu\mathrm{Pa}^2\cdot\mathrm{s}$ for fishes above 2 g and an $\mathrm{SEL_{cum}}$ of 183 dB re 1 $\mu\mathrm{Pa}^2\cdot\mathrm{s}$ for fishes below 2 g (reviewed by Stadler and Woodbury 2009).

The concern, however, was that these regulations were developed without strong science-based data on the physiological effects. This was recognized by calling the regulations interim and allowing for revision of the onset criteria when new science-based data could be applied to the issue. The result of the work reported here therefore, should strongly impact the regulatory environment because the data show that the onset of physiological effects in five taxonomically diverse species for a cumulative exposure is at least 20 dB higher than the levels suggested by the current regulations.

2 Experimental Approach

The experimental methods were described extensively by Halvorsen et al. (2011) and Popper et al. (2013). Fishes were exposed to simulated pile-driving sounds in the HICI-FT, with the major variables being the single-strike SEL ($\mathrm{SEL_{ss}}$) and the number of strikes (either 960 or 1920). By varying the $\mathrm{SEL_{ss}}$ and number of strikes, there was also variation in the $\mathrm{SEL_{cum}}$. The sounds used were actual recordings of impulsive sounds generated by an impact hammer striking a steel shell pile. Six species were used over the course of the experiments, including juvenile Chinook salmon (*Oncorhynchus tshawytscha*), lake sturgeon (*Acipenser fulvecens*; Acipenseridae), Nile tilapia (*Oreochromis niloticus*; Cichlidae), Mozambique tilapia (*Oreochromis mossambicus*; Cichlidae), hogchoker (*Trinectes maculates*; Achiridae), and hybrid striped bass (white bass *Morone chrysops* × striped bass *Morone saxatilis*; Moronidae).

3 Overview of Results

3.1 *Effects on Juvenile Chinook Salmon*

To assess the overall effects of pile driving and develop an understanding of the onset of the physiological impacts, the first study exposed juvenile Chinook salmon to impulsive sounds and subsequently evaluated them for physical barotrauma injuries using an extensive set of criteria (Halvorsen et al. 2011, 2012a). The injuries found in these fish ranged from mild hematomas at the lowest SELs to organ hemorrhage at the highest SELs. Each observed injury was given a weighting based on the physiological severity to the fish. These weightings along with the frequencies of occurrence of these injuries were used to compute a unique biological response-weighted index (RWI) to evaluate the physiological impact of injuries at the different exposure levels. As the $\mathrm{SEL_{ss}}$ and $\mathrm{SEL_{cum}}$ increased, RWI values increased. Based on the results, tissue damage associated with potential mortality occurred when the RWI was >2. In terms of SELs, a RWI of 2 was achieved when the fish were exposed to 1,920 strikes by 177 dB re 1 $\mu\mathrm{Pa}^2\cdot\mathrm{s}$ $\mathrm{SEL_{ss}}$, yielding a $\mathrm{SEL_{cum}}$ of 210 dB re 1 $\mu\mathrm{Pa}^2\cdot\mathrm{s}$, and for 960 strikes by 180 dB re 1 $\mu\mathrm{Pa}^2\cdot\mathrm{s}$ $\mathrm{SEL_{ss}}$, yielding a $\mathrm{SEL_{cum}}$ of 210 dB re 1 $\mu\mathrm{Pa}^2\cdot\mathrm{s}$. These metrics define the thresholds for the onset of injury in juvenile Chinook salmon.

3.2 *Recovery in Juvenile Chinook Salmon*

One of the issues with regard to pile driving is that exposure to sounds may not result in immediate mortality, as shown in Section 3.1. However, it is possible that tissue damage would result in animals succumbing to barotrauma injuries at a later time. Thus, it became important to ask whether fish show increased injuries postexposure and/or whether they could recover from such injuries. To explore this, juvenile Chinook salmon were exposed to simulated high-intensity pile-driving signals to evaluate their ability to recover from barotrauma injuries (Casper et al. 2012; see also Section 3.4). Fish were exposed to 1 of 2 $\mathrm{SEL_{cum}}$ values for 960 pile strikes (217 or 210 dB re 1 $\mu\mathrm{Pa}^2\cdot\mathrm{s}$ $\mathrm{SEL_{ss}}$ values of 187 or 180 dB re 1 $\mu\mathrm{Pa}^2\cdot\mathrm{s}$, respectively). This was followed by an assessment of the injuries immediately or 2, 5, or 10 days postexposure. There were no observed mortalities from the pile-driving sound exposure or during the recovery periods. Fish exposed to 217 dB re 1 μPa^2·s SEL$_{cum}$ displayed evidence of healing from injuries as the postexposure time increased. Fish exposed to 210 dB re 1 μPa^2·s SEL$_{cum}$ sustained minimal injuries that were not significantly different from control fish at days 0, 2, and 10. The exposure to 210 dB re 1 μPa^2·s SEL$_{cum}$ replicated the findings described in Section 3.1 that defined this level as the threshold for the onset of injury in Chinook salmon. Furthermore, these data support the hypothesis that one or two mild injuries resulting from pile-driving exposure are unlikely to affect the survival of the exposed animals, at least in a laboratory environment.

At the same time, it should be recognized that postexposure animals were held in the laboratory where they were not subject to predation and were fed on a regular basis. Whether fish with injuries would survive in the wild, where they have to avoid predation and forage for food, is yet unclear and something that needs further study. Still, it can be argued that the injuries themselves are not mortal, and the critical factor on survival in the wild will be fitness of the individuals.

3.3 Effects on Other Species

Although data on Chinook salmon are very useful, a very critical question is whether the results for that species are applicable to other species. In particular, it is possible that species with different body plans, different sizes, and/or different mechanisms for controlling swim bladder volume would show different effects to impulsive sounds. Of these variables, the most critical is the way that the swim bladder volume is controlled and how easily/quickly the fish can adjust to rapid changes in pressure.

The Chinook salmon are physostomous, meaning that there is a pneumatic duct connecting the swim bladder to the gut. This allows the fish to change the volume of air in the swim bladder by gulping or expelling air. Thus, it became important to also study other physostomous species as well as physoclists or species that have no connection to the gut and only fill or get rid of swim bladder gas via diffusion of gasses through the blood. Finally, comparison with a species not having a swim bladder would enable testing of the hypothesis that much of the barotrauma damage seen in fish is a consequence of the rapidly moving swim bladder walls “striking” nearby tissues.

To test the effects of the swim bladder connection and also to assess the generality of the Chinook salmon results to other species, two studies (Halvorsen et al. 2012; Casper et al. 2013a) performed a comparative analysis of the response to pile-driving stimuli in the lake sturgeon, a species with a physostomous swim bladder; Nile tilapia and hybrid striped bass, species with a physoclistous swim bladder; and the hogchoker, a flatfish without a swim bladder. Fish were exposed to different SELs to determine the levels for onset of visible physiological effects.

The hogchoker demonstrated no observable barotrauma at the maximum sound exposure used, a SEL$_{cum}$ of 216 dB re 1 μPa^2·s (the same level that resulted in mortal injuries in the other tested species), derived from 960 pile strikes and 186 dB re 1 μPa^2·s SEL$_{ss}$. The lack of effect in a species without a swim bladder strongly suggests that the swim bladder plays a major role in barotrauma effects, although it is clear that the results of this study need replication with other species without a swim bladder as well as at even higher SELs.

The lake sturgeon, hybrid striped bass, and Nile tilapia showed a range of injuries. At the maximum sound exposure, the physoclistous species had the highest number and most severe injuries overall compared with the lake sturgeon. Decreases in the exposure levels were correlated with a decrease in the number and severity of injuries for each species. Moreover, as SELs approached the onset of injury threshold found in juvenile Chinook salmon, the hybrid striped bass, Nile tilapia, and lake sturgeon showed injury responses similar to those of the Chinook salmon. Furthermore, the observed injuries became more similar between all species. These results imply that the presence and type of swim bladder correspond with barotrauma injuries at the higher SELs. Therefore, physoclistous fish are more sensitive to the higher SELs than physostomous fish.

3.4 Effects on Fishes of Different Sizes

In setting criteria for the effects of sound on fish, the FHWG concluded that smaller fish are more likely to be affected by exposure to intense sounds than larger animals (Section 1.1), based on an unpublished study of explosives by Yelverton et al. (1975). However, this idea has never been tested with a sound stimulus. Accordingly, Casper et al. (2013a) investigated the effects of exposure to pile-driving sounds on two size groups of hybrid striped bass. The larger striped bass (mean size 17.2 g) were found to have more severe as well as higher numbers of injuries than the smaller fish (mean size 1.3 g). However, fish in each group recovered from most injuries within 10 days of exposure. These results "contradict" the idea that larger fish are less subject to damage by sound than smaller fish, but this still needs further testing in other species and in animals far larger than could be accommodated in the HICI-FT.

3.5 Effects on Inner Ear Tissues

Exposure to intense sounds may have an impact on hearing sensitivity of fishes, resulting in temporary threshold shift (TTS; e.g., Popper et al. 2007; Popper and Hastings 2009). TTS can result in substantial impacts on the ability of fishes to hear and respond to biologically relevant sounds in their environment, including sounds of predators and prey (Slabbekoorn et al. 2010). Thus, it is important to ask whether exposure to pile-driving sounds can result in TTS in fishes. However, with the current technology, actually measuring hearing loss as a result of exposure to pile-driving sounds is very difficult. At the same time, it is known that TTS in fishes is highly correlated with damage to the sensory hair cells of the inner ear (Smith et al. 2006; Smith 2012).

Possible effects on the hair cells from pile-driving sounds were tested in hybrid striped bass and Mozambique tilapia (Casper et al. 2013b). Fish were exposed to 960 pile-driving strikes at one of three treatment levels, 216, 213, or 210 dB re 1 $\mu Pa^2 \cdot s$ SEL_{cum}, and allowed to recover for 2 days. Both hybrid striped bass and Mozambique tilapia exhibited barotrauma injuries such as swim bladder ruptures, herniations, and hematomas to several organs. Hybrid striped bass exposed to the highest sound level had significant numbers of damaged hair cells, whereas no damage was found when fish were exposed at lower sound levels. Significant hair cell damage was found in only 1 out of 11 Mozambique tilapia specimens exposed at the highest sound level.

Results from this investigation led to the suggestion that impulsive sounds such as from pile driving may have a more significant effect on the swim bladders and surrounding organs than on the inner ears of fishes, at least at the SELs used in this study. Thus, the sound levels for the current interim onset of physiological damage to fish are very well below any levels that are likely to result in damage to the inner ear associated with hearing loss. Moreover, it is clear that the onset of damage to the ear (and likely the onset of hearing loss) occurs at SELs that are well above those that are now known to produce the onset of other types of potentially mortal physiological effects.

4 Conclusions on the Effects of Pile-Driving Exposure on Fishes

The results from these studies quantify the effects of impulsive sounds on six species of fish showing wide diversity in body type and swim bladder. They are also the first studies that can provide science-based data useful for developing criteria for impulsive sources. The results define an onset of injury in Chinook salmon at a SEL_{cum} of 210 dB re 1 $\mu Pa^2 \cdot s$ derived from 960 strikes and SEL_{ss} of 180 dB re 1 $\mu Pa^2 \cdot s$ and a SEL_{cum} of 210 dB re 1 $\mu Pa^2 \cdot s$ derived from 1,920 strikes and a SEL_{ss} of 177 dB re 1 $\mu Pa^2 \cdot s$. Although this level of sound exposure at 960 pile strikes showed moderate-to-mortal injuries in the two species with a physoclistous swim bladder, the onset of injury was comparable to that of Chinook salmon at a SEL_{cum} of ~207 dB re 1 $\mu Pa^2 \cdot s$. These results strongly suggest that although other species may be more sensitive and may have a lower threshold than Chinook salmon, the onset of effects is substantially higher than in the current interim regulations. It is also important to note the metrics used to define threshold include the number of strikes and the SEL_{ss} values that yield the SEL_{cum} values.

Major conclusions from these studies are that (1) for all species studied, the onset of barotrauma effects did not occur until the SEL_{cum} was substantially above the current interim regulations; (2) barotrauma injuries were not observed in a species without a swim bladder (hogchoker), at least up to the extent of sound exposure possible in the HICI-FT; and (3) there were differences in the SEL at which barotrauma initially appeared in fishes. In the most sensitive tested species, barotrauma was still not that different from the onset of injury in Chinook salmon at a SEL_{cum} of 207 dB re 1 $\mu\text{Pa}^2\cdot\text{s}$ derived from a SEL_{ss} of 177 dB re 1 $\mu\text{Pa}^2\cdot\text{s}$ and 960 strikes; (4) the onset of damage to the sensory cells of the ear is at levels that are substantially higher than the onset of barotrauma injuries; and (5) the important metrics used to define the impulsive exposure incorporate how the energy accumulated. The three recommended metrics are SEL_{cum}, SEL_{ss}, and the number of strikes.

At the same time, it must be recognized that these results are only for fishes in the acoustic far field where pressure is the dominant stimulus. Because all species of fish also detect particle motion, it is possible that the results might be somewhat different, particularly for the inner ear studies, if the HICI-FT had been run so that the signal was dominated by particle motion. However, because particle motion is only dominant very close to a sound source and the vast majority of fishes exposed to pile driving would be in the acoustic far field, the results from this series of studies are highly applicable to most fishes exposed to pile driving. Moreover, although the sounds used in these studies were from pile driving, the results may be suggestive of what may happen with other impulsive sound sources, such as seismic air guns. Indeed, results from one such study (see Chapter 107 by Popper et al.) suggest that exposure to a single shot from a seismic air gun at levels comparable to those used here had no physiological effect on several species.

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Chapter 16
Review of the Effects of Offshore Seismic Surveys in Cetaceans: Are Mass Strandings a Possibility?

Manuel Castellote and Carlos Llorens

Abstract Displacement of cetaceans is commonly reported during offshore seismic surveys. Speculation concerning possible links between seismic survey noise and cetacean strandings is available for a dozen events but without convincing causal evidence. This lack of evidence should not be considered conclusive but rather as reflecting the absence of a comprehensive analysis of the circumstances. Current mitigation guidelines are inadequate for long-range effects such as displacements and the potential for strandings. This review presents the available information for ten documented strandings that were possibly linked to seismic surveys and recommends initial measures and actions to further evaluate this potential link.

Keywords Anthropogenic noise • Air gun • Marine mammal • Displacement

1 Introduction

There is an increasing level of concern about the effects of anthropogenic sound on the marine environment, particularly the potential effects of widespread offshore seismic surveys on marine mammals (National Research Council 2003; Southall et al. 2009). Multiple reviews have identified offshore seismic surveys as major sources of anthropogenic noise in the ocean and of primary concern to marine mammals (e.g., Hildebrand 2009). However, despite the concern and significant efforts to better understand the effects of noise from offshore seismic surveys on marine

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mammals in the last decade (e.g., Exploration and Production [E&P] Sound and Marine Life Joint Industry Programme), this is still a very controversial scientific field where conclusive results are yet be achieved. Suggestions to link cetacean atypical mass strandings to offshore seismic surveys have been proposed in several events (e.g., Malakoff 2002; Yaipen-Llanos 2012; Southall et al. 2013), involving mysticetes, odontocetes, and both deep-diving and non-deep-diving cetaceans. However, a causal link has not yet been established in any of these cases. This lack of evidence should not be considered conclusive but rather as reflecting the absence of a detailed and comprehensive analysis of the circumstances surrounding these events. A major obstacle when evaluating potential causal links is the fact that most of the available environmental and biological data is limited to near distances from the source that is related to the current recommended mitigation guidelines. Long-range effects such as displacements and the potential for strandings are rarely monitored or considered. This review presents documented evidence of cetacean displacement during offshore seismic surveys for the period 2005–2013 and the publicly available information for ten documented strandings where a link to seismic surveys was suggested. Initial measures and actions to further evaluate this potential link are recommended.

2 Materials and Methods

2.1 Behavioral Effects

An exhaustive search of publications and technical reports related to changes in cetacean behavior during seismic surveys was made for the time period 2004–2013 and is presented in Table 16.1. Reports before 2004 are not considered here because these were included in a similar review by Gordon et al. (2004).

Table 16.1 Documented evidence of cetacean displacement during offshore seismic surveys from 2005 to 2013

Reference	Species and displacement distances
Miller (2005)	Bowhead whales—no distance specified. Beluga whales—10–20 km.
Gailey et al. (2007)	Gray whales—no distance specified.
Weir (2008)	Sperm whales and Atlantic spotted dolphins—no distance specified
Koski et al. (2009)	Bowhead whales—no distance specified
Cerchio et al. (2014)	Humpback whales—no distance specified
Castellote et al. (2012)	Fin whales—285 km
Blackwell et al. (2013)	Bowhead whales—no distance specified
Heide-Jørgensen et al. (2013)	Narwhal (ice entrapments)—200 km

2.2 Mass Strandings

An exhaustive search of publications, technical reports, and news in the media related to cetacean mass strandings potentially linked to offshore seismic surveys was completed. For those events in which seismic acquisition activities were not evident, a search for navigational warnings promulgated by the Worldwide Navigational Warnings Service was made in the region and period where the stranding was reported to identify offshore seismic operations. All the available information for each event is summarized in Table 16.2.

Inspired by the methodology applied by D'Amico et al. (2009), a ranking system for the quantity and quality of available data for each event was developed as a rough metric of the relative level of confidence offered by the data for inferences about the possible role of the offshore seismic survey in a given stranding event ranging from the least robust (1) to the most robust (5). Ranking criteria are as follows: (1) there is a histopathology study available and the results are compatible with a behavioral response to acoustic exposure according to Cox et al. (2006); (2) there is no evidence for an alternative cause of stranding in the histopathology study or postmortem examination; (3) there are no rare species in mass strandings or an increased number of strandings in the area; (4) there was a true atypical mass stranding according to Frantzis (1998); (5) there were offshore seismic operations close to the stranding site (<50 km) or coincident in space and time, with the same species involved in the stranding event (following Cox et al. 2006); and (6) there were offshore seismic operations within 500 km of the stranding site (based on maximum distances where strandings with a suspected seismic survey impact link have been suggested).

3 Results

3.1 Behavioral Effects

See Table 16.1.

3.2 Mass Strandings

See Table 16.2.

Table 16.2 Cetacean mass strandings that have been potentially linked to offshore seismic surveys

Location	Date	Species	Seismic survey 1. Academic, 2. Commercial	Distance (km)	Seismic equipment	Histopathology	Main reference(s)
Galapagos Islands, Ecuador	11 April 2000	*Z. cavirostris* (*n* = 4)	1. *R/V Maurice Ewing*	500	10 Air guns, 4,438 in.^{3} array Subbottom, 3.5 kHz Multibeam, 14–16 kHz	Inconclusive. No brain dissection.	Gentry (2002)
Gulf of California, Mexico	24 September 2002	*Z. cavirostris* (*n* = 2)	1. *R/V Maurice Ewing*	22	20 Air guns, 8,490 in.^{3} array Subbottom profiler Multibeam	No external signs. No necropsy.	Malakoff (2002) and Koski et al. (2003)
Abrolhos Bank, Brazil	March to November 2002	*M. novaeangliae* (*n* = 20)	1. Various by CGG Veritas at Espírito Santo and Campos Basins	32–274	?	No specialized necropsies. Suspected but inconclusive.	Engel et al. (2004)
Falkland Islands, UK	23 January 2004	*G. melas* (*n* = 110)	2. *R/V Geo Pacific* by Desire Petroleum plc	>150	6 Streamers, 3,450 in.^{3}	?	Anonymous (2004) and Richards et al. (2006)
Rota, Spain	9 September 2007	*M. Bidens* (*n* = 2)	1. *R/V L'Atalante* by Spanish Geological Survey (Pérez Carrillo de Albornoz 2007)	45	14–16 Air guns, 3,349 in.^{3} Subbottom profiler, 3.5 kHz Multibeam	No specialized necropsies. Inconclusive. Case under review (A. Fernández, personal communication)	Somoza et al. (2007) and Bellido et al. (2009)

Antsohihy Bay, Madagascar	4 June 2008	*P. Electra* ($n=100$–200)	2. *MV Teknik Perdana* by Exxon Mobil (Van Niekerk 2013)	50	Kongsberg Simrad EM120 12-kHz multibeam.	Secondary interacting factors related to disorientation.	Southall et al. (2013)
Falkland Islands, UK	March 2011	*G. melas* ($n=400$)	2. *MV Polarcus Asima* and *MV Polarcus Nadia* by Rockhopper Exploration plc, Argos Resources Ltd., & Desire Petroleum plc	36	?	?	Anonymous (2011a, b)
Piura and Lambayeque regions, Peru	12 February to 26 April 2012	*D. capensis* ($n=680$) and *P. spinipinnis* ($n=67$)	2. CGG Veritas Vantage by BPZ Energy 1. *R/V L'Atalante* (Anonymous 2012c, d, e)	<460	?	Severe acoustic trauma. Acute systemic gas embolism. Decompression sickness.	Anonymous (2012g) and Yaipen-Llanos (2012)
Anstruther, UK	2 September 2012	*G. melas* ($n=26$)	2. CGG Veritas Vantage by BPZ Energy, Adira by Polarcus DMCC (Anonymous 2012b)	400	?	Apparently healthy condition.	Anonymous (2012a)
Falkland Islands, UK	11 February 2013	*G. melas* ($n=22$)	2. *M/V Ramform Sterling* (FOGL) by Falkland Oil and Gas Ltd. and Noble Energy Offshore	>150	?	Apparently healthy condition.	Anonymous (2012f, 2013)

4 Discussion

4.1 Behavioral Effects

The behavioral responses of cetaceans to seismic survey noise are common and quite variable and occur in most cases at distances exceeding the limits where mitigation measures are applied. Spatial displacement is the most common reaction observed both in the review by Gordon et al. (2004) and in this review (2005 to present time). Displacement has been observed in both mysticetes and odontocetes, including deep divers and coastal and pelagic species. This reaction occurred at wide ranges from hundreds of meters to hundreds of kilometers. Some findings are contradictory (e.g., reports where displacement was not apparent exist but were not included in this review), and the biological consequences of temporary displacements are still largely unknown. However, it must be emphasized that populations could be adversely affected if foraging or breeding periods, orientation including a reduction in hazard avoidance, or social behavior is altered. A behavioral response such as swimming away from an offshore noise source into shallow water could lead directly to stranding. This has been proposed as a potential mechanistic pathway through which naval active sonar may lead to beaked whale mass strandings (Cox et al. 2006), although for deep-diving cetaceans, behavioral responses to sonar directly leading to tissue damage through a change in dive profile, staying at depth, or remaining at the surface longer than normal is a more plausible mechanism (Fernández et al. 2004). Neither of these two mechanisms can be ruled out in the context of seismic survey noise and changes in cetacean behavior. Even if acoustic characteristics of noise sources from naval active sonar and air guns are extremely different, it should not be ignored that air gun array use is often (if not always) combined with high-power active transducer sources such as multibeam, single-/dual-/split-beam, or subbottom profilers. These are often overlooked because of the directional nature of their acoustic outputs, but a signal in excess of 120 dB can often reach tens of kilometers, and when taken into consideration, the acoustic footprint of a survey increases significantly in both the spatial and spectral domains (e.g., Wood et al. 2012; Zykov 2012) and sometimes even in the time domain if sources are not used concurrently. None of the current mitigation guidelines applied worldwide for offshore seismic operations consider the risk of strandings related to behavioral reactions. Spatial displacement leading to stranding cannot be currently identified without dedicated stranding monitoring plans during and after seismic surveys. Similarly, strandings as a consequence of decompression sickness cannot be currently identified without stranding response plans, including specialized necropsy methods during and after seismic surveys.

4.2 Mass Strandings

Ranking results did not identify any mass stranding in which the relative level of confidence for inferences about the possible role of an offshore seismic survey reached the maximum score of 6. Although the lack of information or public unavailability mostly determines the results of the ranking analysis presented in Table 16.3, six mass

Table 16.3 Relative level of confidence

Criteria	Ecuador	Mexico	Brazil	Falkland 2004	Spain	Madagascar	Falkland 2011	Peru	Scotland	Falkland 2013
Histopathology compatible with behavioral response to acoustic exposure according to Cox et al. (2006)	0	0	0	ND	0[a]	0	ND	1	0	0
No evidence for an alternative cause of stranding in histopathology study or postmortem examination	1	1	1	ND	1	1	ND	1	1	1
Rare species in mass strandings or increased number of strandings in site	1	1	1	0	1	1	0	1	0	0
True atypical mass stranding according to Frantzis (1998)	0	0	0	0	0	1	0	1	0	0
Offshore seismic operations close to the stranding site (<50 km) or coincident in space and time with same species involved in a stranding	0	1	1	0	1	1	0	0	0	0
Offshore seismic operations within 500 km from the stranding site	1	1	1	1	1	1	1	1	1	1
Relative level of confidence for inferences about the possible role of the offshore seismic survey	**3**	**4**	**4**	**1**	**4**[a]	**5**	**1**	**5**	**2**	**2**

The relative level of confidence (scale of 1–6) offered by the data for inferences about the possible role of the offshore seismic survey in a given stranding event is based on the six criteria described in Section 2.2

ND no data available

[a] Studies are underway that could impact the level of confidence

strandings reach a level of confidence for inferences about the possible role of the offshore seismic survey of rank 3 or higher on a scale of 6. The Madagascar event, ranked 5, involved melon-headed whales, a species that was also involved in an embayment event in Hanalei Bay, HI, in 2004 (Southall et al. 2006) coincident with naval sonar operations. A high-power 12-kHz multibeam echosounder system used as part of a seismic survey, before the onset of any air gun activity, has been identified as the most plausible and likely behavioral trigger for this mass stranding (Southall et al. 2013). The Peru event, also ranked 5, can be defined as an atypical mass stranding and occurred while two seismic vessels were operating at ~500 km from the stranding region. The histopathology study is compatible with severe acoustic trauma similar to the diagnosis in other mass strandings linked to naval sonar operations. The events in Spain, Mexico, and Ecuador exclusively included beaked whales, a deep-diving odontocete group known to be particularly sensible to sound and related to most of the mass strandings linked to naval sonar operations (Cox et al. 2006).

5 Conclusions

This review emphasizes the paucity of available information in suspected mass strandings, leading to low levels of confidence for inferences about the possible role of offshore seismic surveys. In all ten cases included in this review, critical information was nonexistent or not publicly available. Although none of the ten cases reviewed here is conclusive, this and previous reviews present more than enough evidence to confirm that offshore seismic operations alter the behavior of cetaceans. The potential to cause a mass stranding, according to the current knowledge in the context of naval sonar operations, cannot be ruled out. This problem calls for the urgent development and adoption of a precautionary approach and a proactive attitude from both operators and regulators. Offshore seismic surveys must be undertaken with appropriate regulations and codes of practice based on precautionary assumptions comprising negative effects such as mass strandings. Mitigation protocols must consider the risk for mass strandings as well as the collection and reporting of appropriate information during and after seismic operations to document any potential link to cetacean mass strandings. Such an approach would stimulate stakeholders to strive to expand and refine our knowledge about the effects of seismic surveys on cetaceans and help clarify how regulation should best be adapted to reduce the risks to marine diversity while allowing sustainable exploitation of natural resources within realistic limits.

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Chapter 17
Addressing Challenges in Studies of Behavioral Responses of Whales to Noise

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Abstract Studying the behavioral response of whales to noise presents numerous challenges. In addition to the characteristics of the noise exposure, many factors may affect the response and these must be measured and accounted for in the analysis. An adequate sample size that includes matching controls is crucial if meaningful results are to be obtained. Field work is thus complicated, logistically difficult, and expensive. This paper discusses some of the challenges and how they are being met in a large-scale multiplatform project in which humpback whales are exposed to the noise of seismic air guns.

Keywords Behavioral response • Underwater noise • Impacts of noise • Whales • Seismic

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1 Introduction

If our operations in the ocean are to continue in the way that our societies expect, we must find ways of doing this with a minimum impact on the environment. This, of course, requires an understanding of the impacts, how they are caused, and the contribution of the many factors that affect the impacts. Behavioral response studies (BRSs) are used to assess the behavioral reactions of animals to some stimulus, and in the context of the effects of noise on aquatic life, it might be expected that the stimulus is the underwater noise of some human activity. Noise, however, is usually only one factor involved in the behavioral response to the human activity. The noise is an indicator of the presence of the source and the response may be to the source itself or to what it implies. The response may depend on the proximity of the source and the direction in which it is moving relative to the subject animal. The response may be modified by the social context: what other animals, particularly conspecifics, are present and how they are interacting. For whales, the social category of the subject (e.g., male, female with calf) is likely to be important and the response may also be modified by environmental conditions such as water depth and distance from the coast. Wind speed and, therefore, background noise levels may also be significant.

Earlier studies on the behavioral response of whales to noise show such a wide variation in the received noise level at which behavioral changes were observed that it becomes almost meaningless to talk of a simple threshold of response in terms of received level or “noise dose.” Richardson et al. (1995) cite many such studies that were carried out on baleen whale species. The threshold noise levels observed for a reaction varied over a range of 50 dB, the lowest being at levels that were only audible because of the low levels of ambient noise at the time. Humpback whales responded to playback of tones at levels that were so close to the background noise that some of the playback was probably inaudible (Dunlop et al. 2013). It might be said that if a whale can hear a sound, there is the potential for it to show some behavioral reaction. The response may depend more on the nature of the noise and what it implies about the source than the received noise level itself. For example, playback studies with beaked whales found a stronger reaction to the playback of killer whale sounds (one sample) than to the playback of simulated sonar sounds or noise (Tyack et al. 2011). A suggestion was that the greater response to killer whale sounds may have been because they are predators of beaked whales.

The wide range of noise levels for the behavioral response means that reactions can occur over a very wide range of distances from the source. This makes it very difficult to manage the impact of activities that are likely to cause behavioral responses. However, it is generally accepted by scientists and regulators that a behavioral response itself is not necessarily of concern unless it is likely to have longer term biological consequences or significance. This has been reviewed extensively by the National Research Council (2005) and led to a framework of a model relating responses to biologically significant effects. However, the knowledge needed to apply this or any other model to be useful is very limited.

This paper discusses how some of these challenges are being met in project BRAHSS (Behavioural Response of Australian Humpback whales to Seismic Surveys) and presents insights gained from completing two of the four planned experiments in which migrating humpback whales were exposed to the sounds of small air gun arrays.

2 Experimental Design

Suitable experimental design is the key to a successful BRS. Sample size and adequate controls are crucial. Whales show a wide range of behaviors as part of their normal activity, and detection of a response requires the statistical comparison of behavior during “active” trials (i.e., with the stimulus) with that during control trials (without the stimulus) to account for other potential effects. Without an adequate sample size and controls, it may not possible to determine a clear response to the stimulus even if the response is real. The sample size and controls must be adequate to deal with the variability in response caused by the many factors that affect the response. One approach to dealing with multiple variables is to conduct trials in which some variables could be held constant. This would simplify the analysis but requires multiple studies to ensure that the effects of all variables are tested. Many variables cannot be held constant in studies at sea.

In a well-controlled experiment, the control sample should be the same as the active sample in every aspect except for one: the presence or absence of the stimulus. However, maintaining such tight experimental control is almost impossible in studies of whales at sea. It should be possible to match the active and control sample sizes, the stimuli, and the nontemporally varying environmental conditions. It is much more difficult to match the social context and the relative positions of whales and the source throughout the experiment. This inability to mimic conditions for both active and control samples leads to very complex analysis.

All experimental variables likely to affect response must be measured. This leads to complex, prolonged multiplatform experiments that are logistically difficult and expensive. The dilemma in the experimental design is that every additional sample value increases the cost of the project, so there are pressures to minimize the sample size. A more productive way of dealing with this is to recognize that there is some threshold sample size that needs to be achieved if the project is to be successful. Anything less and the funds, time, and effort are wasted, apart from the experience gained. Hence it is important to estimate in advance the sample size required for success.

For BRAHSS, we estimated the sample size required by conducting a power analysis on the results of a previous study at the same site with the same population (Dunlop et al. 2012, 2013). The stimulus was different (tones compared with air gun sounds), which required the assumption that the response would be similar to both stimuli, and the adoption of a larger sample size ($n = 15$) than that indicated by the power analysis ($n = 12$) in an attempt to deal with the uncertainty of using a different type of noise. In the experiments, the active sample was matched with as many controls in which the air gun array was towed but not firing. Because it was possible that the whales might react to the vessel even if the array was not firing, further controls were obtained in the absence of the vessel.

Two experiments have been completed off the east coast of Australia. These experiments used a small air gun array with various capacities and thus radiated sound levels, including a single 20-in.^{3} air gun, a 140-in.^{3} air gun array, and a 30-min "ramp-up"' that involved four steps at 20-, 60-, 140-, and 440-in.^{3} capacity. The sample size for each "treatment" exceeded 15, including all control treatments.

One major problem with many BRS experiments is pseudoreplication, where incorrect conclusions may be drawn about the response to a specific stimulus or its function within a population or species without true replication of the experiment. The BRAHSS project thus involves experiments off the east and west coasts of Australia, providing two populations of whales and two environments with different physical properties (e.g., water depth and transmission loss) as well as a variety of stimuli. Different capacities provided by an air gun array give different source levels and frequency spectra. The third and fourth experiments will be off the west coast of Australia. The third will use the same air gun array and the same experimental design as used off the east coast. The fourth will use a full seismic array. Therefore, varying the populations, site, and stimuli provides protection against pseudoreplication as well as providing a large sample size with which to test or account for other factors that may contribute to the response.

The two humpback whale populations and their normal behavior, use of sound, population dynamics, and biology have been extensively studied for many years. This provides a basis for inferences about the longer term biological significance of behavioral responses.

3 Field Measurements

3.1 Measurement of Behavior

The two completed experiments in BRAHSS were off the east coast of southern Queensland where humpback whales pass close to shore as part of their southward migration. Over the dimensions of the study site (~20 km along the shore and 10 km seaward from the shore), whales followed meandering tracks and showed behavior similar to that on the breeding grounds further north. Whale groups (typically 1–3 individuals) were selected for focal follow and were tracked, and behaviors were noted using theodolites on high points on the shore and from small boats following the groups. Theodolites provide accurate tracking without the disturbance of a following boat, but we found that some behaviors (e.g., some blows) that were seen from the boats were missed. Comparison of land- and boat-based observations will allow us to determine the effects of disturbance in boat focal follows as well as allow us to account for missed behaviors from land observations. The forthcoming experiments off western Australia will be too far offshore for land-based observations, so we will be relying on the small-boat observations.

DTAGs were used in BRAHSS, but the limitations imposed by the logistics and time required to attach tags and then recover them after each trial meant that we could not obtain a robust sample size. They do, however, provide valuable behavioral data on dive behavior and underwater movement that could not be obtained otherwise.

3.2 Measurement of Received Noise Levels and the Acoustics of the Site

Acoustic recording tags attached to whales generally provide an effective way of measuring the received noise levels at the whales if they are capable of recording the full sound signal across the frequency range and adequately above noise. For air gun sounds where this is substantial energy at low frequencies (down to 10 Hz or less), flow noise on a moving tag may contaminate the recordings, limiting the usefulness for air gun signals. Hence we relied on other methods for estimating received levels. In any case, as noted in Section 3.1, it was not possible to obtain an adequate sample size with tags.

We used both fixed and drifting recording systems to record the acoustic field at various positions throughout the site. These were designed to minimize differential movement relative to the water and were treated to minimize the vortex shedding that generates flow noise. Transmission loss was measured over many paths throughout the site and an empirical model was developed. Received sound levels at whales were estimated from the received level at the nearest recording system using the transmission loss model.

If the proximity of the source is a significant factor in the response, a noise-level dose response will vary between locations and the results determined in one location may not be usefully applied to other locations. Including the distance of the source as a variable in the analysis will be a significant improvement, but because the received level is correlated with distance, this may not resolve the relative contribution of the two variables. Using more than one source level will be a further improvement because this would provide more than one received level for each distance. Better still would be to do the study at two different locations that differ in the transmission loss. We have adopted these approaches in BRAHSS with two experiments off the east coast of Australia and two experiments planned off the west coast, and measurements indicate that the loss is significantly different between the sites.

Measurements at the east coast site showed some small areas of anomalous transmission loss where the loss increased very rapidly over short distances. The effect is that any whale on the other side of one of these areas relative to the source would have received a far lower level than otherwise for the same distances that were effectively shielded from the noise of the source. This effect would significantly confound observations of the response without knowledge of these areas. These areas of anomalous transmission could only have been detected by the detailed measurements that were made.

Recordings of the sound field during the experiments are required to put the results into context. These include the vocalizations of whales within the area and the ambient or background noise. Whale vocalizations are part of the behavioral context of the focal follow whales. We used a fixed long-baseline five-hydrophone array to track vocalizing whales. Ambient noise has the potential to mask the sounds from the stimulus. Ambient noise varies commonly by ~20 dB, and this would vary the audible distance of a source by a factor of 10 for typical sound transmission conditions. If the responses occur at low received levels, they will depend on the ambient noise levels at the time of observation, and this would confound the results unless the ambient noise is measured and included in the analysis. Our recording systems were set to obtain recordings with the two different gains required to cover the higher level signals from the air guns and the lower level ones from the ambient noise.

4 Analysis and Results

The BRAHSS experimental design attempted to achieve a balanced and matching set of active and control samples in a number of ways. The treatment for the day was randomly chosen (using random block design) and the whale groups for focal follow were randomly chosen as much as possible (although the focal groups used were usually the ones that happened to be in the area when the trial was due to start). After the groups were followed for 1 h (the preexposure phase), the beginning of the treatment phase was called regardless of where the group was positioned. However, despite these attempts at sample randomization and balance, in some cases, there were differences between the active and control groups. To illustrate an imbalance between the distribution of active and control samples, we give an example of the bias in one of the experiments (the 20-in.[3] experiment).

Despite our attempt to randomize the conditions, some biases in sample distributions did occur. It turned out that in some cases, the groups in the control sample were, on average, closer to the source vessel at the start of the exposure compared with the groups in the active sample. Table 17.1 summarizes the proximity of the groups to the source vessel during the first 10 min of the 1-h exposure phase (T1 phase).

These examples illustrated that despite considerable efforts to minimize bias, some does occur and has to be dealt with in the analysis. Having to account for differences in condition between control and active samples adds complexity to an already complex analysis. In addition, measured variables such as dive behavior were found to be significantly related to other factors such as water depth and social context (the social composition of the group, the distance of the nearest neighbor, and the distance of the nearest singer). These too must be accounted for in the analysis model.

Table 17.1 Proximity of the source vessel to the focal groups

Treatment	*n*	Proximity (m)
Active east	17	7,784 ± 4,435
Active north	16	9,230 ± 4,955
Control east	12	5,670 ± 2,840
Control north	15	4,750 ± 2,885

Values are means ± SD of the first 10 min of exposure (T1 phase) to the 20-in.^{3} air gun towed northward toward the migration and eastward across the migration

5 Conclusions

Studying the effects of noise on whale behavior presents many challenges. Well-designed experiments, with adequate sample size and the necessary controls to obtain reliable results, are complex, logistically difficult, and expensive. The experimental design should be able to detect and measure any change in whale behavior as well as determine the factors that drive this change in behavior. Some factors will be related to the noise exposure, such as received level and proximity of the source, but the behavior may also depend on other factors such as the social context and the physical environment. Attempting to account for all experimental, social, environmental, temporal, and measurement predictor variables leads to a complex analysis model. The results also need to be placed into the context of the normal behavior of the whales to aid in evaluating the biological significance of the response. It is also evident that BRSs are multidisciplinary. The many activities required for a successful experimental design, execution, and analysis require expertise from a range of disciplines in biology and physics. In studies with whales, the biology requires expertise in animal behavior, experimental design and statistical analysis, mammal hearing and auditory perception, and population dynamics, whereas the physics requires expertise in sound transmission in the ocean, ambient sea noise, sound generation, and signal detection. To be effective, the team of investigators needs to have adequate expertise in the main areas with access to experts in the remaining areas, as is the case with BRAHSS.

Acknowledgments We thank the many people who contributed to the Behavioural Response of Australian Humpback whales to Seismic Surveys (BRAHSS) project and took part in the experiments. More than 70 people were involved in the experiments (see www.BRAHSS.org.au for all names). Anne Goldizen provided advice on studying animal behavior and Simon Blomberg provided advice on the statistical modeling. Michael Williamson and Chandra Salgado Kent also contributed. Geokinetics, Inc. (Brisbane, Australia), provided and operated the air gun array for the second experiment. The BRAHSS project is funded by the Joint Industry Programme on Exploration & Production (E&P) Sound and Marine Life (JIP) and the United States Bureau of Ocean Energy Management (BOEM). The JIP is managed by the International Association of Oil and Gas Producers (OGP). The Joint Industry Sponsors are ExxonMobil, Chevron, Eni, Statoil, ConocoPhillips, BG Group, BHP Billiton, Santos, Woodside, and the International Association of Geophysical Contractors. Additional sponsors are Origin Energy, Beach Energy, and AWE Ltd.

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Chapter 18
Measurements of Operational Wind Turbine Noise in UK Waters

Samuel Cheesman

Abstract The effects of wind farm operational noise have not been addressed to the same extent as their construction methods such as piling and drilling of the foundations despite their long operational lifetimes compared with weeks of construction. The results of five postconstruction underwater sound-monitoring surveys on wind farms located throughout the waters of the British Isles are discussed. These wind farms consist of differing turbine power outputs, from 3 to 3.6 MW, and differing numbers of turbines. This work presents an overview of the results obtained and discusses both the levels and frequency components of the sound in several metrics.

Keywords Underwater sound • Wind turbines • Operational noise • Behavioral effects

1 Introduction

The underwater noise produced by wind turbines can take many forms during the lifetime of a wind farm. During the construction phase, piling of the turbine foundations is known to produce very high levels of noise that are detectable for many tens of kilometers from the source (Bailey et al. 2010). Fewer surveys of the noise caused by operational wind farms have been conducted in the past (Betke et al. 2004; Tougaard et al. 2009), but they do raise the possibility of mild avoidance reactions.

Madsen et al. (2006) said that the disturbance caused by operational noise from wind farms is unlikely to produce a significant effect on marine mammals, although further work such as playback studies is necessary, and to quantify the noise from future, more powerful turbines. Accordingly, this work describes the noise from the current generation of more powerful 3- to 3.6-MW UK wind farms in a similar way

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to how Nedwell et al. (2007b) described a number of 2- to 3-MW UK wind farms. The noise from each wind farm was measured during a survey conducted as part of the license requirement for construction.

2 Materials and Methods

2.1 *Wind Farms Surveyed*

Each of these wind farms were located in shallow, coastal waters (<20 m depth), and each of the surveys were conducted within the last 7 years. The wind farms surveyed were (1) Lynn and Inner Dowsing Wind Farm, which is located in the entrance to the Wash near the coast of Lincolnshire. It consists of 54 turbines that have a power rating of 3.6 MW. Measurements were taken in water depths of 8–20 m. The survey was conducted on 16–18 February 2011; (2) Barrow Offshore Wind Farm, which is composed of 30 wind turbines that have a power output of 3 MW and is located in the East Irish Sea near Barrow-in-Furness. The survey was completed on 19–20 December 2006, 30 January 2007, and 01 February 2007; (3) Gunfleet Sands Wind Farm 1. Gunfleet Sands now consists of two phases; the survey was completed during the first phase. This section is located in the northern part of the Thames Estuary near Clacton-on-Sea and is made of 48 turbines each capable of outputting 3.6 MW. Measurements were taken in water depths of 4–19 m. The survey was conducted on 17–19 April 2011; (4) Kentish Flats Wind Farm, commissioned in 2005 and located in the North Sea close to the coast of Kent. It consists of 30 turbines, each with a rating of 3 MW. The turbines are in water depths of 3–5 m. The survey was conducted on 25 May 2007; and (5) Robin Rigg Wind Farm. This wind farm consists of 60 turbines with a power output of 3 MW each and measurements were taken in water depths of 5–20 m. The survey was conducted on 19–22 March 2011 and 3–4 April 2011.

2.2 *Measurement Methods*

Each survey was conducted on a small vessel, generally 15–20 m in length, either a monohull or catamaran. Whenever a location where measurements were to be taken was reached, the boat captain first determined the depth of water using the echo sounder mounted on the boat. After this, the engines were cut and any electronic devices such as the inverter or the echo sounder that could produce noise were also turned off, with the exception of the radio for emergencies. No anchor was deployed because it may have produced metallic noises, so the boat was allowed to drift.

The hydrophone was deployed over the side of the boat. It was held at midwater depth, suspended from an “antiheave” or “spar” buoy. This is a long cylindrical buoy designed to minimize the movement of the hydrophone in the water column when it came into contact with waves or turbulence. The hydrophone and antiheave buoy were fed out on a cable and allowed to drift freely away from the survey vessel for a short distance while measurements were being recorded, thus minimizing the amount of flow noise. Once a measurement had been completed, the hydrophone was retrieved and the vessel was restarted and moved to the next position. Measurements of the wind speed were taken using a handheld anemometer.

Measurements were taken in different locations and patterns throughout each wind farm. First, a reading of the background sound level around the wind farm was taken. To ensure that the noise from the wind farm did not encroach on the background recordings, the background reading was taken at a distance of 10–20 km from the nearest turbine. The operational noise survey consisted of measurements taken either in transects from a specific turbine or on long drifts through the center of the wind farm. The transect measurements were first taken close to one of the turbines on the boundary of the wind farm, then at increasing distances away from the turbine, away from the wind farm. In one instance, measurements from the same turbine were taken on successive days with differing wind speeds to assess the variation under different meteorological conditions.

2.3 Measurement Equipment

For each survey, one of three Brüel & Kjær type 8106 hydrophones was used, with a usable frequency range of 1–120 kHz and a sensitivity of −173 dB re 1 V/μPa. A custom-made amplifier (Subacoustech Ltd.) was used to amplify the signal between 0 and 40 dB and the signal was sampled at a rate of 350,000 samples/s using a National Instruments type 6062E or type 6216 data-acquisition device before storage on a laptop computer. A grounding plate was attached to one of the metal BNC connectors of the amplifier and then placed in the water to minimize static and 50-Hz main power noise.

2.4 Data Analysis

Frequency spectra of the sound were calculated and then corrected for the unique frequency response of each hydrophone. Root-mean-square (rms) sound levels and sound exposure level (SEL) figures were also calculated using software developed by Subacoustech. To estimate the impact ranges of any sound recordings, the $\mathrm{dB_{ht}}$ values were calculated, which are an estimate of the sound level as a particular species might hear it (Nedwell et al. 2007a). The level of sound against range was plotted, and lines of best fit, based on minimizing the least squares error, were added to estimate the source level and transmission loss of the sound from the turbines.

The $\mathrm{dB_{ht}}$ is a metric that allows an estimate of how a sound may influence different species of fish and marine mammals. It incorporates an estimate of a species' hearing using a peer-reviewed audiogram to determine the extent to which the animal in question may react to the sound. This involves creating a filter based on the audiogram in much the same way as the dB(A) is calculated for humans in air. Nedwell et al. (2007a) gave the following criteria for dB_{ht} and levels of disturbance: 90 dB_{ht} causes a significant avoidance reaction by a majority of individuals in a subject population and 50 dB_{ht} causes a minimal avoidance reaction in a limited portion of the population. Between these two values, a mixed response is likely to happen, with a portion of individuals reacting at varying degrees depending on context.

This paper presents calculated dB_{ht} levels and uses them to calculate 50-dB_{ht} ranges (the level at which a minimal avoidance by a species could be expected) for two species. These are *Gadus morhua* (cod), a fish with good hearing compared with other species of fish (using the audiogram from Chapman and Hawkins 1973), and *Tursiops truncatus* (bottlenose dolphin), using the audiogram from Johnson (1967).

3 Results

Sound pressure measurements were recorded from at least four turbines in each of the wind farms surveyed. The sound spectra recorded at a distance of ~30 m from a turbine in each wind farm surveyed are shown in Fig. 18.1. The noise from the turbines can be seen to be concentrated in the region of 10–1,000 Hz, with many tonal peaks. In this region on the frequency scale, at Lynn and Inner Dowsing Wind Farm, the sound is between 20 and 30 dB above the background level, with very little, if any, sound energy extending above 1,000 Hz.

The sound levels for each transect were calculated and then plotted against range. A line of best fit was added to the data, allowing an estimation of a source level and

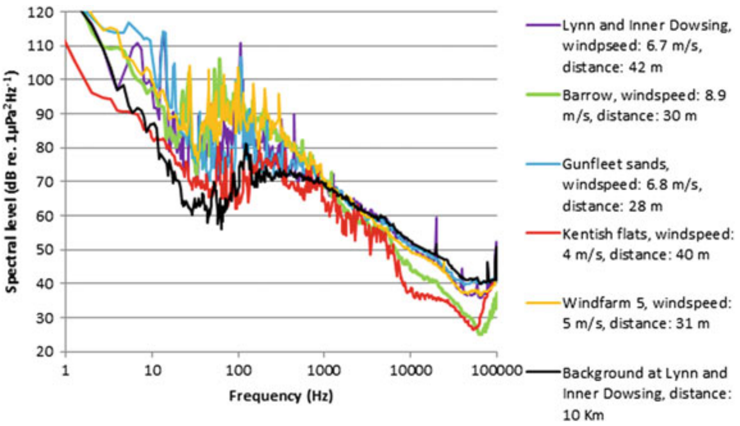

Fig. 18.1 Power spectral density of noise at a distance of ~30 m from turbines at each wind farm studied. The majority of noise above background from the turbines is in the range of 10–1,000 Hz, with many tonal peaks

transmission loss. One such transect is shown in Fig. 18.2. These data were recorded on 17 February 2011 from 9:30 to 10:30 am. Also shown on the graph are the maximum, mean, and minimum 1-s rms background noise levels recorded at a distance of 10 km from the wind farm.

An attempt was made to calculate the source level for each wind farm and transect. The dB_{ht} values were also calculated for *Gadus morhua* and *Tursiops truncatus*, and a line of best fit was added to these data, allowing an estimation of a source level in the same way as shown in Fig. 18.2. The range to 50 dB_{ht} was then taken to be the point at which the line of best fit falls below the level of 50 dB_{ht}. This data are summarized in Table 18.1. Sections showing N/A indicate that not enough measurements close to the turbine and above background level were able to be gathered to calculate a source level with confidence.

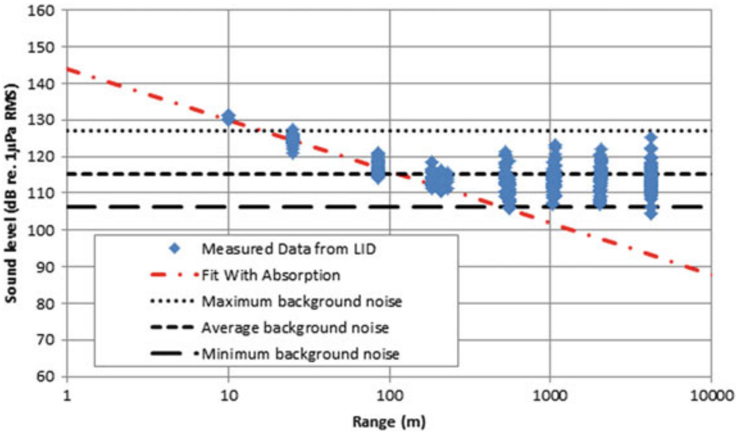

Fig 18.2 Sound level measurements plotted against range for a turbine measured on 17 February 2011 in a wind speed of 6.7 m/s. The source level of the turbine was 144 dB re 1 μPa root-mean-square (RMS) and the transmission loss was a factor of 14. *LID* Lynn and Inner Dowsing Wind Farm

Table 18.1 Maximum source levels and impact ranges from each of the wind farms surveyed

Wind farm	Maximum source level (dB re 1 μPa rms)	Maximum range to background level (m)	Range to 50 dB_{ht} *Gadus morhua*	Range to 50 dB_{ht} *Tursiops truncatus*
Lynn and Inner Dowsing	142	200	200	500
Barrow	N/A	N/A	40	N/A
Gunfleet Sands	160	200	20	150
Kentish Flats	N/A	N/A	N/A	N/A
Robin Rigg	N/A	N/A	100	N/A

N/A not enough measurements close to the turbine and above background level were able to be gathered to calculate a source level with confidence, *rms* root-mean-square, *dB_{ht}* metric that allows an estimate of how a sound may influence different species of fish and marine mammals

4 Discussion

Estimation of the source level was difficult for many of the wind farms, which indicates that the sound produced by the turbines was itself not of a high sound level. At times of increased wind speed, the noise from the turbines did increase. This was evident at the Lynn and Inner Dowsing Wind Farm where the increase in wind speed from 3.4 to 7.1 m/s showed an increase in the apparent source level of 4 dB. Unfortunately, the increase in wind speed meant that sea became too dangerous on which to work, meaning measurements at higher wind speeds to confirm this assertion were not possible.

The two wind farms for which a source level of the unfiltered noise from the turbine could be calculated turned out to be the two most powerful ones, the wind farms that had 3.6-MW turbines installed compared with the 3-MW turbines of the other wind farms. There is a large variation in source level between these two wind farms. All of the calculated $\mathrm{dB_{ht}}$ levels were below 90 $\mathrm{dB_{ht}}$, indicating that a significant avoidance reaction, based on the criteria described by Nedwell et al. (2007a), would not occur. However, the range to 50 $\mathrm{dB_{ht}}$, the extent to which a minimal avoidance reaction may occur, does extend up to 500 m in the case of *Tursiops truncatus*. Southall et al. (2007) also have criteria for the effects of noise on marine mammals based on a weighted SEL metric. The highest source level for any of the wind farms studied for "medium-frequency cetaceans" (as defined in Southall et al. 2007), of which *Tursiops truncatus* is a member, was estimated to be 134 dB re 1 $\mu\mathrm{Pa}^2\cdot\mathrm{s}$, which falls well below the auditory injury criteria for "nonpulses" described in that paper. Southall et al. (2007) did not specify criteria for avoidance by medium-frequency cetaceans of nonpulses.

In some instances, the range to 50 $\mathrm{dB_{ht}}$ is higher than the range to background noise level. This occurred because once the data were filtered using the audiogram of the species being studied, certain elements of the sound from the turbines, which were previously obscured by elements of the unfiltered data like the tonals shown in Fig. 18.1, could be distinguished. This effect means that the range to the background $\mathrm{dB_{ht}}$ level is much longer, up to 8 km in the case of the cod at the Lynn and Inner Dowsing Wind Farm and that the sound from some wind turbines is still able to be detected at large ranges, although it is not thought that it causes any behavioral effects at this point because it is below 50 $\mathrm{dB_{ht}}$.

The measurement procedure was able to produce recordings of noise from wind turbines of sufficient quality to estimate the source level of several turbines and, consequently, the range to 50 $\mathrm{dB_{ht}}$, giving an indication of their effects on two species. The noise from waves and turbulence was able to be mitigated with the use of the antiheave buoy but was not completely eliminated, as can be seen from the large amount of noise below 10 Hz in Fig. 18.1. However, this is not thought to be a barrier to assessing the effects on fish because most fish audiograms of *Limanda limanda* (dab; Chapman and Sand 1974) and *Salmo salar* (salmon; Hawkins and Johnstone 1978) do not show a large sensitivity at very low frequencies of this order, and it would be difficult to mitigate this level of noise further with a hydrophone suspended from a boat.

The power of wind turbines in UK waters have increased over the years, from round 1 wind farms using 2-MW turbines installed in wind farms such as Scroby Sands to round 1 and 2 wind farms with turbines of 3 and 3.6 MW described here. Round 3 wind farms are currently still in the consent phase and many include the possibility of higher power turbines being used further out at sea in locations of higher wind speeds and deeper waters.

5 Conclusions

The operational noise from five wind farms located in UK waters has been measured. The measurements recorded were over a wide frequency range, allowing measurements to be taken over the full fish and marine mammal auditory range. After estimating the 50-$\mathrm{dB}_{\mathrm{ht}}$ impact range for *Gadus morhua* and *Tursiops truncatus*, there was an indication that some mild disturbance could be made to these species up to 200 and 500 m, respectively, from some turbines based on the 50-$\mathrm{dB}_{\mathrm{ht}}$(Species) criteria. There was also an indication that sound levels were dependent on turbine power level and wind speed, which means that future, more powerful wind farms may produce a higher sound level.

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Chapter 19
A Bioenergetics Approach to Understanding the Population Consequences of Disturbance: Elephant Seals as a Model System

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Abstract Using long-term empirical data, we developed a complete population consequences of acoustic disturbance (PCAD) model and application for northern elephant seals. We assumed that the animals would not successfully forage while in a 100-km-diameter disturbance region within their foraging and transit paths. The decrease in lipid gain due to exposure was then translated to changes in birth rate and pup survival. Given their large foraging range, elephant seals were resilient to such a disturbance, showing no population-level effects. However, similar track analysis showed that given their more coastal nature, California sea lions were within a 25-km-diameter region of disturbance more often.

Keywords Population consequences of acoustic disturbance • Acoustic disturbance • Behavior • Sea lion • Demography

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1 Introduction

Although we have developed sophisticated tools and approaches to determine the range of sounds organisms can hear and their responses to underwater sounds (Costa et al. 2003; Tyack et al. 2011; Reichmuth and Southall 2012), we have a difficult time assessing when and if these responses are biologically "meaningful." In the context of conservation and management, a biologically meaningful response is one that results in a change at the population level. The National Research Council Committee on Population Consequences of Acoustic Disturbance (PCAD) developed a framework that detailed how behavioral responses to sound may affect life functions, how life functions are linked to vital rates, and how changes in vital rates cause population change through a series of transfer functions (National Research Council 2005). Although logistical limitations preclude assessment of these transfer functions for most marine mammals, there are a few species, such as elephant seals (*Mirounga leonina* and *M. angustirostrus*), for which data are available to parameterize these transfer functions. Extensive research on their at-sea movement patterns, reproductive biology, and demography have been carried out (Robinson et al. 2012; Schick et al. 2013). The species also provide a relatively simple system because at-sea disturbance only reduces foraging opportunities, not mating or offspring care, which occur on land. Furthermore, the relationship between maternal mass and pup wean mass and subsequent pup survival is well documented as is the threshold between body condition and natality (Arnbom et al. 1993; McMahon et al. 2005). Therefore, elephant seals provide an unusual opportunity to test the PCAD model in its entirety.

The PCAD model proposed a variety of approaches that could be used to detect a biologically meaningful response, including a bioenergetics model where the costs associated with disturbance are linked to reductions in foraging success (Costa 2012; New et al. 2013, 2014). This approach assumes that changes in behavior compromise the maternal condition by reducing the energy gain (interrupting foraging behavior) and increasing the energy expenditure (cost of avoidance); these costs lead to a compromised adult condition, reduced natality and energy delivery to offspring, higher rates of offspring mortality, and, at the extreme, increased adult mortality. In elephant seals, the maternal condition can be measured directly as mass or lipid content, providing an accurate empirical measurement and a strong foundation for this analytical framework (Crocker et al. 2001). Furthermore, changes in buoyancy over their foraging trip can be used to estimate the daily lipid mass gain while at sea (Schick et al. 2013). Using this approach, New et al. (2014) provided a test of the PCAD model for southern elephant seals by assuming that a female would not be able to forage throughout the period of disturbance. This decrease in foraging resulted in a reduction in the female's lipid mass gain, limiting her ability to invest in her pup. The pup would then be weaned at a smaller size and would thus have lower survival. Last, they ran simulations of various periods of disturbance to estimate the changes in population growth rate in southern elephant seals given estimated reductions in pup survival.

Although the New et al. (2014) study was the first implementation of the PCAD model with robust demographic data, it was limited in that the simulated disturbance only occurred during a predetermined period starting at the end of the foraging trip and did not take into account spatial variation in the disturbance and/or variations in the behavior of individuals. Here we extend the PCAD bioenergetics model developed by New et al. (2014) to (1) estimate changes in reproductive rate with disturbance and (2) incorporate spatial and temporal variability in movement patterns during two phases of the postmolting foraging trip of northern elephant seals. Finally, because elephant seals are highly migratory and forage widely, we compared their potential levels of exposure to the highly coastal income breeding California sea lion *Zalophus californianus*.

2 Materials and Methods

We simulated the population impact of a disturbance within the foraging range of northern elephant seals by first estimating the proportion of the population that would be exposed to a disturbance and then examined what proportion of their foraging trip would be affected if the disturbance occurred within both a densely populated foraging and transiting region (Fig. 19.1). We used a worst-case scenario in which any exposure resulted in zero foraging success over the period and region of exposure. Using data from individuals whose fat gain had been modeled over their entire foraging trip (Schick et al. 2013), we then subtracted the lipid mass they would have gained over those days from their total gain over the trip. We then

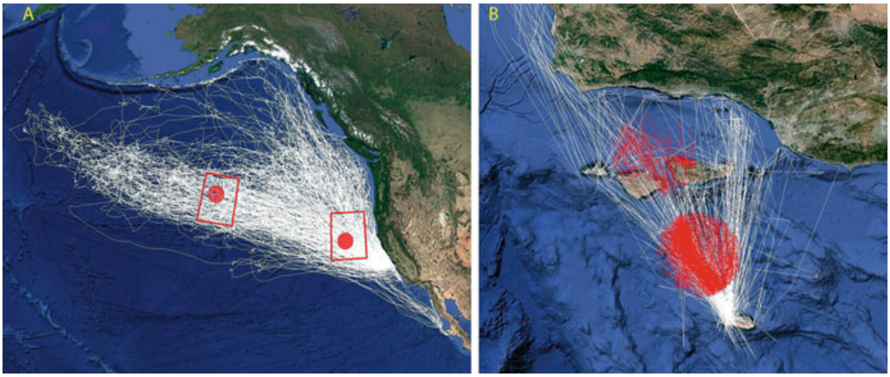

Fig. 19.1 (**a**) Migration tracks of 105 northern elephant seal females. *Red boxes*, areas where the 100-km-diameter circle were randomly sampled. *Left box* and *circle* is in the primary foraging region and *right box* and *circle* is in the transit region. (**b**) Tracks of 39 California sea lion females on their foraging trips from their breeding colony on San Nicolas Island. *Red circle* shows all of the tracks that passed through a 25-km disturbance region during transit and *red* area just above the islands shows the tracks that passed through a 25-km disturbance zone while animals were foraging (imagery from Google Earth)

estimated how that reduced body condition would affect reproductive rate, pup wean mass, and subsequent pup survival. For comparative purposes, we ran a similar simulation with California sea lion females that were tagged on San Nicolas Island, CA, to examine the risk to acoustic exposure only.

2.1 Disturbance

To estimate what proportion of northern elephant seals would be affected by a continuous disturbance that is limited to a specific geographic region, we chose 25-km- and 100-km-diameter circles and assumed that any individual passing through this region would not successfully forage while exposed to the disturbance (Fig. 19.1). These circles were randomly placed within the transit corridor and within a region that had the highest density of foraging female elephant seals. Iterating the random placement of the disturbance 1,000 times, we used the tracks of 105 female elephant seals to measure how much time each female spent in the 2 disturbance regions. Similarly for California sea lions, we used 39 tracks of adult females that were tracked on San Nicolas Island (Costa et al. 2010). Because the sizes of the disturbance were large in comparison to the home range of the individuals, we did not perform multiple iterations of disturbance. Instead, we chose a disturbance with its center either near the center of the colony (100 km transiting) or near the center of the transit or foraging area (25 and 100 km foraging; Fig. 19.1).

2.2 Life History Data and Analysis

We used lipid mass as the metric of maternal body condition that affects reproductive rate and pup wean mass. In turn, pup survival to 1 year is a function of wean mass. Using the truncated cones method, the lipid mass of adult females was measured before and after the postmolt foraging trip, standardized by correcting for time on land before and after the trip (Crocker et al. 2001). Postweaning pup mass was also collected and back calculated to mass on the day of weaning (L. Schwarz, unpublished analysis). Because females that do not pup usually have shorter or longer foraging trips compared with females that pup (Robinson et al. 2012), the reproductive rate was measured as a logistic function of lipid mass gain rate ($n = 115$). For a small subset of females ($n = 11$), both maternal lipid mass and pup wean mass were collected. We used a linear regression to estimate wean mass as a function of maternal lipid mass (Arnbom et al. 1993; Crocker et al. 2001). Using mark-recapture data of pups with a measured wean mass ($n = 1{,}334$), pup survival was estimated as a quadratic function of wean mass, also accounting for tag loss as a function of wean mass (Schwarz et al. 2012). Bayesian posterior parameter estimates for all functions were calculated using a Metropolis-within-Gibbs sampler with vague, noninformative prior estimates (Schwarz 2008). For a subset of elephant seals ($n = 26$), we modeled the lipid composition of seals throughout their migrations using empirical body composition measurements combined with drift rate (buoyancy) data on a daily scale (Schick et al. 2013). We used the 100-km disturbance simulations to subtract any lipid gain they may have accrued while in the disturbance area from their final lipid mass. We then used results from the above analyses to estimate subsequent changes in reproductive rate, pup wean mass, and pup survival.

3 Results

3.1 Movements Through Disturbance

For the 100-km disturbance in the high-density foraging zone, 73% of the 105 sampled individuals passed through at least 1 disturbance area. They spent a mean of 6.4 days in the disturbance zone, with 1 female spending up to 87 days in a disturbance area. Although a greater number of individuals passed through the disturbance zone when it was placed within the transit corridor, the duration of exposure was less. All individuals passed through the disturbance in the transit corridor, spending a mean of 3.6 days, with 1 female spending 83 days.

Of the subset of 26 females whose daily lipid gain was estimated, 5 were never exposed and 21 would have experienced some decrement in body condition ranging from no effect to a loss of up to 60% of 1 individual's normal lipid stores (Fig. 19.2).

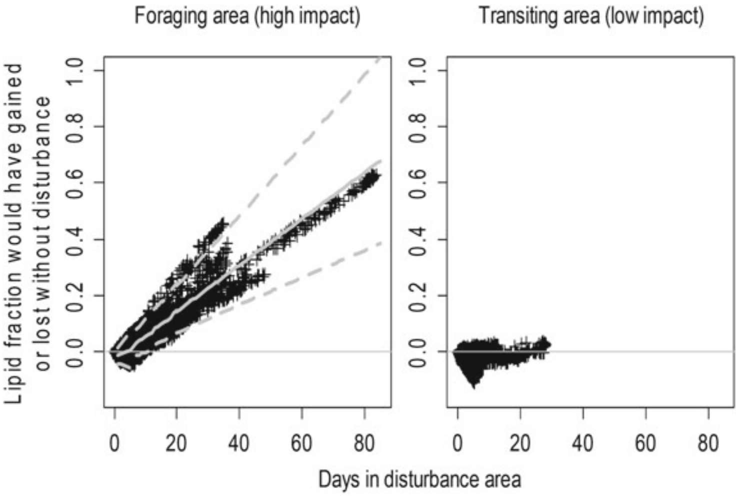

Fig. 19.2 Relative proportion of lipid that would have been gained while the animal was in the disturbance region for elephant seals found in the high-density foraging region and the transit region. We assumed that this lipid would not be gained because animals would not be foraging while in the disturbance region

Animals exposed during the transit phase of their migration experienced little or no loss in body condition (Fig. 19.2). Although the overall mean final lipid mass at the end of the foraging trip, when females come on shore, was similar regardless of the level of disturbance (none: 169.3 kg; transit: 169.3 kg; forage: 167.5 kg), the minimum estimated final fat mass was lowest in the foraging area (none: 142.6 kg; transit: 138.6 kg; forage: 87.9 kg).

3.2 Relating Disturbance to Reproduction and Pup Survival

Given the relationship between fecundity and female condition (Fig. 19.3), we were able to convert the projected loss of body condition to a potential reduction in reproductive output. The reproductive rate for these 26 healthy elephant seals when disturbance was not present would be 0.995 (0.975–1.0; mean [95% posterior interval]). Although the high rate was estimated from their fat mass gain, empirical pupping data matched the estimates; all 26 females pupped at the end of the foraging trip in which they were tracked. The normal reproductive rate was in comparison to the estimate of 0.994 (0.971–1.0) for the same animals exposed to disturbance in the foraging area, whereas those animals exposed during transit had no change in reproductive rate. Similarly, given the known relationship between maternal mass and weaning mass, these 26 females' pups would normally weigh 139 kg (97–186 kg) at weaning, and for those that were exposed in the foraging region, they would weigh 138 kg (95–185 kg), with an undetectable change in the wean mass for those exposed during transit. Finally, given the known relationship between weaning mass and survival to the first year of life, pup survival from weaning to 1 year old was the same regardless of exposure (no disturbance: 0.961 [0.847–0.997]; transiting: 0.961 [0.847–0.997]; foraging: 0.960 [0.836–0.998]). Overall, these changes in female fecundity and pup survival would have no effect on the population status of northern elephant seals.

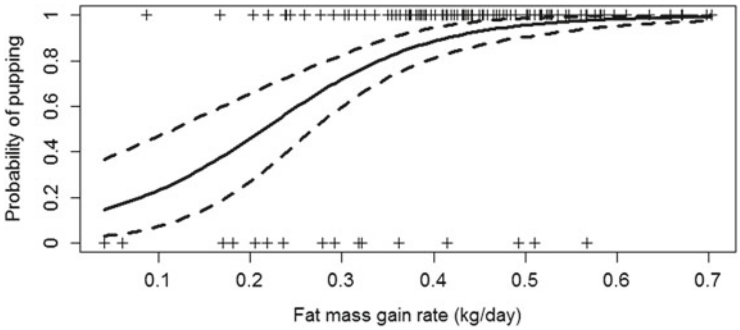

Fig. 19.3 Probability of an elephant seal female giving birth to a pup as a function of her mass gain rate while foraging at sea

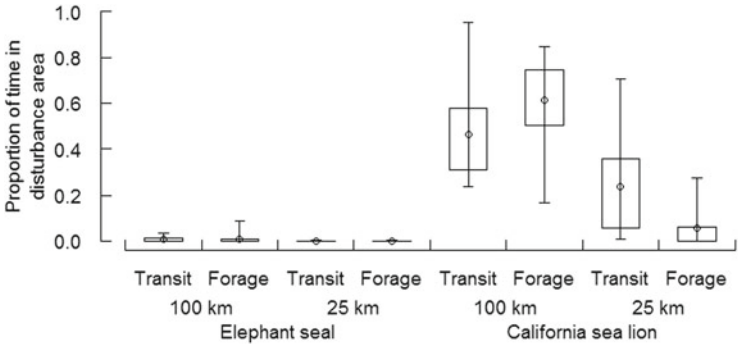

Fig. 19.4 Relative proportion of time that elephant seals and sea lions spent in 100- and 25-km-diameter disturbance areas during transit and foraging phases of their foraging trips

3.3 Comparison to California Sea Lions

Of the 39 California sea lions tracked, all passed through the 100-km transit disturbance zone, and all but one passed through the 100-km foraging disturbance area. Fewer individuals were found within the 25-km disturbance areas (38 transiting and 25 foraging). Individuals spent 26.2 ± 11.7 (mean ± SD) days in the 100-km transit disturbance area and 36.9 ± 15.2 days in the 100-km foraging disturbance area. With a smaller 25-km disturbance area, individuals spent 6.5 ± 16.3 days transiting with disturbance and 3.4 ± 6.2 days foraging with disturbance. Overall, the proportion of time spent within a disturbance area was considerably larger for California sea lions compared with elephant seals (Fig. 19.4).

4 Discussion and Conclusions

We anticipated that given the northern elephant seals' comparatively large foraging range, a large disturbance area (100 km) would be required to have any effect on their foraging success. Regardless, our simulation was a worst-case scenario because we assumed a complete cessation of foraging behavior. This is not likely to occur because animals will probably avoid the area and look for other foraging opportunities. We also did not include any potential compensatory increases in foraging effort that may occur outside the disturbance region (Costa 2012). Such a change in behavior is relatively straightforward for elephant seals that forage along the North Pacific transition zone where resources are widely dispersed over a rather large area (Robinson et al. 2012) and may be applicable to other wide-ranging species. Although this foraging pattern is the most common for northern elephant seals, there are individuals who forage in coastal regions and spend most of their time in a localized region. A disturbance within such a region would have a much greater impact on an individual. This is likely the case for the female who could potentially be exposed to the disturbance for more than 80 days. However, because these females represent a small proportion of the population, the population-level effect of the disturbance is low. Although demographic data were not available for California sea lions, our results show that a coastal species like sea lions with a more limited foraging range would have a greater potential to be impacted by a disturbance within their home range.

The reproductive rates and pup survival rates without disturbance do not represent the overall rates for the population because the 26 females selected for this analysis were not randomly drawn. They were all healthy and did produce pups after their tracked foraging trips. We will continue to refine these estimates by including more females in the analysis. However, even with overall lower demographic rates, they are unlikely to decline much further in the presence of the modeled disturbance compared with what we have reported here. Namely, for this type of disturbance, we would see little-to-no effect on the population status of northern elephant seals.

It is important to note that pup survival relationships have high levels of posterior uncertainty, mostly because factors other than maternal lipid mass and wean mass affect pup survival. For example, the relationship between maternal lipid mass and weaning mass is quite variable. This is not unexpected because weaning mass may also be affected by many random processes on the colony, such as the degree of disturbance on the colony, weather, interactions with other females, and the quality of the harem master. Furthermore, survival to year one is affected by processes other than weaning mass. Some pups may find high-quality prey patches or, conversely, may be weaned during a poor year when resources are less available. All of these features weaken the link between maternal condition and pup survival. However, the quantified uncertainty is a realistic representation of how disturbance that reduces foraging ability will likely impact northern elephant seal populations and other widely foraging species.

Acknowledgments This paper was developed in association with the Office of Naval Research-supported population consequences of acoustic disturbance/population consequences of disturbance (PCAD/PCOD) committee and was supported by Office of Naval Research Grant N00014-08-1-1195, the Exploration and Production (E&P) Sound and Marine Life Joint Industry Programme of the International Association of Oil and Gas Producers, ExxonMobil and Shell oil companies, and the Ida Benson Lynn Chair in Ocean Health. We also acknowledge the University of California Natural Reserve System and the rangers of Ano Nuevo Reserve.

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Chapter 20
Singing Fish in an Ocean of Noise: Effects of Boat Noise on the Plainfin Midshipman (*Porichthys notatus*) in a Natural Ecosystem

Sarika Cullis-Suzuki

Abstract When it comes to hearing and vocal communication in fishes, the plainfin midshipman (*Porichthys notatus*) is perhaps best understood. However, distinctly lacking are studies investigating communication of *P. notatus* in its natural ecosystems and the effects of noise on wild fish populations. Here, an exploratory look into both is discussed. By monitoring a population of wild *P. notatus* off British Columbia, Canada, call patterns were distinguished, the function of communicative sounds was identified, and midshipman vocalizations in agonistic encounters with natural predators were evaluated. A preliminary investigation into the effects of boat noise on wild midshipman is also described.

Keywords Vocalization • Predator–prey interactions • Communication • In situ

1 Introduction

Ship traffic along the Pacific northwest coast is substantial (Halpern et al. 2008) and is only set to increase (Heise and Alidina 2012). Already, marine transport has contributed significantly to ocean noise. "Shipping is probably the most extensive source of noise in the oceans, especially along major shipping channels (e.g., from Alaska to California for supertankers carrying oil)" (Popper 2003). The Pacific Northwest is also the coastal habitat range for many distinct fish species, including those that depend on sound to communicate and derive information from their auditory scene (Popper and Hastings 2009b). One such species is the plainfin midshipman (*Porichthys notatus*; Arora 1948; see Fishbase.org), a highly vocal fish whose call frequency overlaps that of boat noise (e.g., from large ships); this makes

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apparent the potential for boats to mask or impede fish communication, which could, in turn, have cascading effects up and down the food chain, including impacts on predators (see Slabbekoorn et al. 2010).

1.1 Fish and Ships

Until relatively recently, the vast majority of research on the effects of anthropogenic noise on marine life has focused on the impacts on marine mammals (e.g., Barrett-Lennard et al. 1996; Ford et al. 2000; Kastak et al. 2005; Mulsow et al. 2011). Over the last few years, however, more studies have emerged documenting the potential impacts of noise on other marine life, including crustaceans, cephalopods, and even coral (Department of Fisheries and Oceans Canada 2004; Vermeij et al. 2010; André et al. 2011; Simpson et al. 2011; Wale et al. 2013). In particular, anthropogenic noise as it affects fishes, noting their wide range, abundance, and diversity, is currently being explored (McCauley et al. 2003; Anderson et al. 2011; Holles et al. 2013). Potential impacts of noise on fish are now known to extend from direct physical harm, including stress and hearing loss (Amoser and Ladich 2003; McCauley et al. 2003), to indirect results such as altered group formations and spatial distributions (e.g., schooling behavior; Pearson et al. 1992; Slotte et al. 2004; Sarà et al. 2007) and masked communication (Vasconcelos et al. 2007); such effects are not limited to the adult forms (see Simpson et al. 2004; Wright et al. 2008; Radford et al. 2011) and could impact fitness (e.g., Sarà et al. 2007). Human-induced noise in the ocean encompasses acute sources like pile driving and sonar as well as more continuous noise such as from shipping (Popper and Hastings 2009b). Recent articles stress the importance of understanding the less studied and lower intensity noise produced from shipping because it is both chronic and globally widespread (Popper 2003; Halpern et al. 2008; Slabbekoorn et al. 2010; Ellison et al. 2012).

1.2 Predators and Prey

Predator–prey interactions increase the stability of ecosystems (Allesina and Tang 2012). However, the difficulties of assessing such dynamics in the wild are many, especially within multipredator scenarios (Lima 2002; Handegard et al. 2012). Although data are limited, when it comes to the effects of noise on fish and predator–prey relationships, some studies suggest that noise can affect fish both as predators and as prey; as predators, noise could impede their foraging competence (Purser and Radford 2011) and as prey, fish could alter their vocalizing behavior in the presence of nearby predators (Remage-Healey et al. 2006). Studies on other organisms show evidence for increased vulnerability to predation under boat noise conditions (Chan et al. 2010). More research on fish is needed, however, because, “Data are completely lacking in fish, but based on insight from very few and very different animal species, we believe that anthropogenic masking effects on predator–prey relationships could be widespread” (Slabbekoorn et al. 2010).

1.3 A Singing Fish

The plainfin midshipman, also known as talkative fish, singing fish, and canary fish (Kasumyan 2009), is found along the Pacific coast of North America and belongs to the family Batrachoididae, a highly vocal group of fish collectively known as toadfish. These fish produce sounds by contracting a pair of sonic muscles attached to their gas-filled swim bladders (Bass 1996; Sisneros 2009a). *P. notatus* has two adult male morphs, type I (alpha male) and type II (sneaker male), which vary in vocal abilities among other characteristics (Bass 1996; Sisneros 2012). Type I males produce several agonistic sounds, including the grunt (also produced by females), the grunt train (a sequence of short repetitive grunts), and the growl (Bass et al. 1999). Of most interest and currently best understood, however, is the hum, a distinct and prolonged vocalization emitted only by alpha males and associated with reproduction (Brantley and Bass 1994; Bass 1996; McKibben and Bass 1998; Sisneros and Bass 2005; Sisneros 2009b). All documented vocalizations produced by midshipman have fundamental frequencies at or just below 100 Hz (Weeg et al. 2002).

During the late spring and summer months, *P. notatus* migrates up into the intertidal zone from hundreds of meters deep to lay eggs and nest (Arora 1948; Sisneros 2012). Thus, it makes a particularly convenient research subject for in situ predator–prey studies; when exposed at low tides, *P. notatus* can be accessed with relative ease (Brantley and Bass 1994; McKibben and Bass 1998) and, being highly territorial, alpha males do not leave their nests, which helps in documenting predator visits (e.g., through a stationed camera).

2 Study

“Finally, and perhaps most importantly, there is a need for behavioral studies that actually examine the responses of wild fish to anthropogenic sounds. Almost all studies to date have involved caged fish” (Popper and Hastings 2009a). The purpose of this investigation was to analyze vocal communication of *P. notatus* within its natural ecosystem and to explore the effects of boat noise on wild populations.

2.1 Methods

The study site for this research was located in a small bay on the east coast of Quadra Island in the Strait of Georgia, off the north Pacific coast of Canada. Although the bay itself is relatively protected, the Strait of Georgia is an area highly impacted by human activities, including shipping (Ban et al. 2010). From late April to late August 2012, continuous underwater recordings were taken with a hydrophone (HTI-96 MIN; www.hightechincusa.com) secured to the bottom of the ocean floor near nesting midshipman at tidal depths varying between 1 and 20 ft. Baseline information on vocalizations and call patterns of midshipman as well as salinity and temperature data over an entire breeding season was then collected. The following year, between 7 and 27 June 2013, 15 distinct *P. notatus* nests, each guarded by an alpha male, were monitored and recorded over the course of 15 days. Midshipman nests were chosen at the lowest daytime tides and based on the presence of a nest-guarding midshipman, eggs, and accessibility. This experiment was unique in that, by using two cameras simultaneously, the effects of boat noise on prey and on predators could be observed concurrently; a "drop camera" (created for this research and fitted with LED lights and red light filters) was positioned in front of each nest (Rubow and Bass 2009) along with a microvideo camera, also fitted with LED lights and red light filters (MVC2120WP-LED; www.microvideo.ca), which was set up for observing *P. notatus* underneath rocks (Lee and Bass 2006). This double-camera setup allowed clear, simultaneous viewing of *P. notatus* in its nest as well as predator appearances outside the nest. Two hydrophones (HTI-96-MIN) were also set near nests, one synced with the drop camera and the other recording audio independent (see Fig. 20.1 for the experimental setup.) Live audio and video data were streamed through waterproof cables back to a proximate research station (e.g., Wardle et al. 2001), where they were recorded onto external hard drives. All cables of video cameras and hydrophones were at least 300 ft long to accommodate reaching from nest sites to research station.

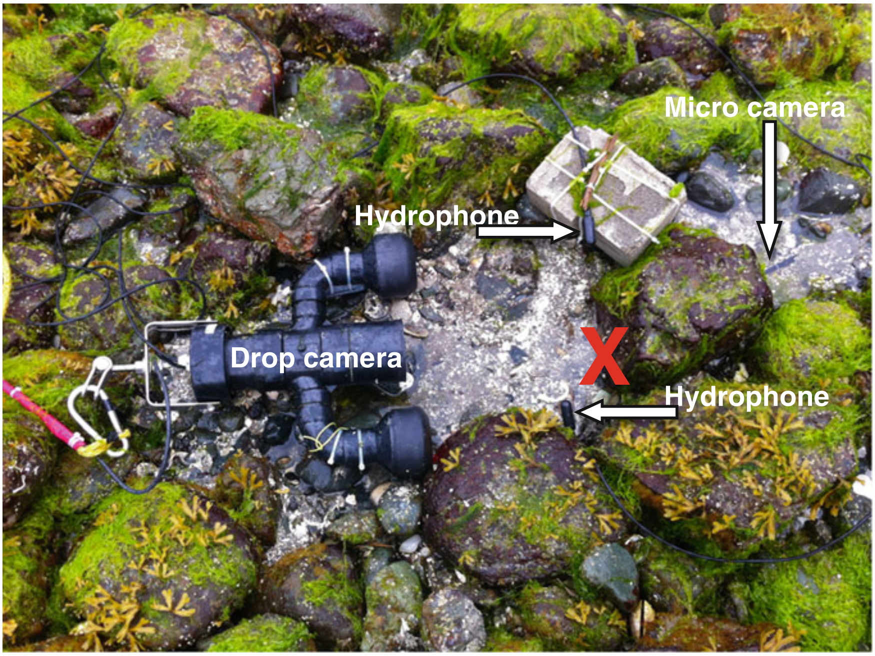

Fig. 20.1 Field setup. X denotes nest entrance

Boat noise experiments were conducted over the same 15 days in 2013, and each experiment lasted under 1 h. At 5 pm on experiment days, trials began; the treatments were boat noise, boat (engine off), and control. The treatments were randomized and lasted 16 min each. Boat noise was provided by a 14-ft aluminum boat with a 9.9-hp engine driven in real time by a research volunteer near the field site (i.e., within 100 ft of the nest). After the trials were completed, video and audio data collection continued until the following morning to keep documenting fish behaviors and ecosystem dynamics along with any potential longer term effects from noise (Picciulin et al. 2010).

3 Preliminary Findings

Although data analysis is currently still in progress, preliminary findings include

(1) an extremely high diversity and abundance of *P. notatus* predators in natural ecosystems. Midshipman predators ranged from crustaceans to fish to pinnipeds. Predator visits occurred continuously throughout the day and night. Most predators were interested in *P. notatus* eggs, although some, e.g., birds, otters, mink, actively hunted *P. notatus* adults;

(2) a *P. notatus* defense, which often included lunging and vocalizing concurrently, that was highly effective across most species of predators. Although grunts and growls are thought to be agonistic sounds emitted by *P. notatus* when threatened by other conspecifics (Brantley and Bass 1994; Bass and McKibben 2003), the use of such vocalizations against heterospecifics has not been documented before;

(3) *P. notatus* predators that might be affected by boat noise. Early investigations point to a possible change in visitation patterns by certain species of midshipman predators under boat noise conditions;

(4) the effects of boat noise on guarding alpha male *P. notatus* that are not obvious. Further assessment, including statistical analysis, is needed;

(5) continuous nest guarding by male *P. notatus* that is essential for egg survival. Multiple video recordings revealed that the absence of a guarding midshipman male, even for a few minutes, resulted in the rapid decimation of egg clutches by predators; and

(6) new insights into wild calls. Discoveries corresponding to natural vocalization patterns included evidence that growls and grunts occur during the day (in contrast to previous studies, e.g., Rice et al. 2011), and other findings (e.g., high maximum grunt numbers/train; see Maruska and Mensinger 2009).

4 Importance of Field Studies: Looking at the Ecosystem

Over the last few decades, studies describing the neural hearing mechanisms of *P. notatus* and how it responds to sound, both pressure and particle motion, have been undertaken (e.g., Weeg et al. 2002; Sisneros and Bass 2003; Bass and Ladich 2008; Sisneros 2009b; Suk et al. 2009; Zeddies et al. 2010, 2012; Alderks and Sisneros 2011). Yet what we know scientifically about this fish is almost entirely derived from laboratory work; data on the natural life history and ecology of *P. notatus* are startlingly few. This is concerning because data collected in the lab could be contradicted by those collected in situ (Myrberg and Spires 1972). "Most importantly, it is not possible to extrapolate in any way from studies of caged fish to wild animals" (Popper and Hastings 2009a).

Laboratory studies are infinitely easier to perform than field studies. Controlling all factors in the wild is near impossible, not to mention the added complexity of temperate marine ecosystems. Yet it is precisely because of these complicated, interwoven factors found only in the ocean that we must observe systems as they are found, in the wild. More research in the field would help fill in knowledge gaps and guide us toward more appropriate hypotheses.

5 Ongoing Work/Future Studies

Data analysis for this study is still in progress, yet the role of sound in predator–prey interactions under both natural and boat noise conditions is already apparent. Although *P. notatus* is known to have many predators, both underwater (otters, seals) and on land (herons, gulls, eagles, mink; DeMartini 1988; Elliott et al. 2004; Love 2011), this will be the first attempt to quantify the diversity and abundance of such predators. Furthermore, this research provides the first evidence that *P. notatus* vocalizes agonistically against heterospecific predators; correlations between midshipman vocalization type and predator type will be further investigated and success rates of predators will be determined, all under natural conditions and when exposed to boat noise. Vocalizations and sounds obtained from long-term acoustic datasets (e.g., for seasonal patterns and anthropogenic noise disturbances and including a comparison of vocalizations of *P. notatus* populations in low and high boat traffic environments) will continue to be analyzed. Finally, field studies on other fish species in other natural ecosystems, using similar coupled acoustic-optic setups (see Rountree et al. 2006), would yield highly informative data and should be pursued.

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Chapter 21
Detection of Complex Sounds in Quiet Conditions by Seals and Sea Lions

Kane A. Cunningham, Brandon L. Southall, and Colleen Reichmuth

Abstract To test how accurately baseline audiometric data predict detection of complex stimuli, absolute detection thresholds for frequency-modulated (FM), amplitude-modulated (AM), and harmonic stimuli were obtained for one *Phoca vitulina* (harbor seal) and one *Zalophus californianus* (California sea lion) at frequencies spanning the functional range of hearing. These thresholds were then compared with a priori predictions based on the tonal audiograms of these subjects. Predicted thresholds were accurate for most FM signals and for AM signals for the California sea lion. Predictions were unreliable for harmonic signals for both species and for AM signals for the harbor seal.

Keywords California sea lion • Harbor seal • Pinniped • Threshold • Hearing

1 Introduction

Basic audiometric data are often used to predict the effects of anthropogenic noise on marine mammals. Because these audiometric data are generated using pure-tone or narrowband stimuli, such predictions are based on the assumption that hearing thresholds for simple sounds are similar to hearing thresholds for natural sounds with complex spectral and temporal features. In unmasked conditions, a species-specific audiogram consisting of a series of absolute detection thresholds for pure-tone or very narrowband signals at frequencies spanning the functional range of hearing can be extrapolated to predict the detectability of a simple signal. However,

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biologically relevant sounds, including animal vocalizations, tend to exhibit certain complex features. How the presence of such complex features affect signal detectability and, therefore, the accuracy of predictions made based on audiogram data remains largely unknown.

Complex spectral and temporal features, particularly amplitude modulation (AM), frequency modulation (FM), and the presence of multiple harmonics, are found in many animal vocalizations across a variety of species. Not surprisingly, specific structures have been identified within the auditory system to detect and process these common features (Suga 1992). As an example, recordings obtained from the auditory cortex of the cat show that individual neurons are sensitive to different rates and directions of FM (Mendelson and Cynader 1985) and that neuronal firing rates modulate with the AM of a stimulus (Nelken et al. 1999). The presence of such structures suggests that, at least for certain species, the detection of complex signals may be fundamentally different from the detection of pure-tone or narrowband signals, and there is some empirical evidence suggesting that this is indeed the case. Turnbull and Terhune (1994), for example, found that both human and harbor seal listeners had lower detection thresholds for ascending frequency sweeps compared with the same stimulus with a descending structure. Such findings underscore the need to further investigate how well audiograms and other baseline audiometric data predict detection of complex sounds.

Understanding such auditory phenomena in animals is more important now than ever because the levels of anthropogenic noise in the ocean have risen rapidly over the past century, with largely unknown effects on marine mammal species (Southall et al. 2008). To understand and anticipate these effects, knowledge of how marine mammals perceive complex stimuli is needed. This study focuses on the ability of two pinnipeds, one California sea lion and one harbor seal, to detect complex sounds in quiet conditions. Behavioral detection thresholds were obtained for AM and FM signals as well as for harmonic complexes at a set of frequencies spanning the functional range of hearing. These were then compared with a priori predictions made based on the tonal audiograms of these individuals. The results of these comparisons can help determine how baseline hearing data can best inform regulatory criteria for marine mammal noise exposure as well as provide valuable insight into how the phocid and otariid auditory systems process complex sounds.

2 Psychoacoustics

All thresholds were obtained behaviorally using a go/no-go testing procedure. In this procedure, the subject swam down to a listening station where a trial light turned on to indicate the beginning of a 4-s trial interval. On signal trials, a stimulus was presented at random within the trial interval; on a catch trial, no stimulus was presented. For a signal trial, a correct response consisted of the subject moving from the listening station to touch a nearby response target with its nose. For signal-absent (catch) trials, a correct response consisted of the animal remaining on the listening station until the trial light was extinguished. Correct responses of either type were reinforced at an equal ratio with a fish reward. Incorrect responses, including touching the response target when no signal was presented (false alarm) and remaining at the station when a signal was played (miss), were never reinforced.

Sound pressure levels of the psychoacoustic stimuli were calibrated before each session. Within a session, the levels were adjusted using a staircase procedure with a 4-up/2-down step size until a minimum of 5 hit-to-miss transitions were completed. Cumulative false alarm rates were maintained at rates greater than 0% and less than or equal to 25% by manipulating the signal-to-catch ratio within a session. This ensured a stable response bias across all testing conditions. Sessions in which the subject was under poor stimulus control, as evidenced by excessively high false alarm rates or excessively variable miss levels, were discarded. Subjects were run until within-session estimated threshold levels were consistent across three sessions. All thresholds were calculated at the 50% correct response level using the average of the hit-to-miss transitions.

3 Results by Stimulus Type

The accuracy of a priori predictions based on audiogram data varied according to stimulus type as well as by species. In general, FM stimuli were best predicted by audiogram data, whereas predictions for harmonic stimuli were least successful. The accuracy of predictions for AM stimuli varied by subject.

3.1 FM Stimuli

FM signals comprised an octave-band linear upsweep and were generated at four center frequencies: 500, 2,000, 16,000, and 38,000 Hz. These frequencies were chosen to span the functional range of underwater hearing for these species. Octave-band sweeps were chosen to ensure that the FM bandwidth exceeded one critical band at all center frequencies (Southall et al. 2003). Sweep duration was 500 ms for all frequencies.

Absolute detection thresholds for these FM signals were well predicted by the audiogram. A priori predictions were made based on linear interpolation of the two nearest audiogram data points for each subject that bracketed the center frequency of the FM sweep (Reichmuth et al. 2013). All observed thresholds were within 5 dB of the predicted value for both subjects, with the exception of the sea lion threshold that was at a 38-kHz center frequency, which was 7 dB lower than predicted.

This discrepancy for the sea lion at 38 kHz is likely due to the fact that the sweep crosses the region of the sea lion audiogram where hearing sensitivity is decreasing rapidly with increasing frequency, i.e. the high-frequency roll-off. Because the bandwidth of the octave-band sweep is greater than a single critical band and because the auditory integration time is likely less than the duration of the signal at this frequency (Kastelein et al. 2010), the earlier lower frequency portion of the sweep is probably determining the observed threshold, resulting in the lower than expected value. That is to say, this stimulus at threshold is likely perceived by the sea lion subject as a shorter duration sound with a lower center frequency.

3.2 AM Stimuli

To create AM stimuli, a pure-tone carrier was modulated sinusoidally with a modulation depth of 6 dB. Four carrier frequencies, identical to the center frequencies of the FM stimuli, were used: 500, 2,000, 16,000, and 38,000 Hz. To test the possibility of increased detectability of common natural signals, a 50-Hz modulator frequency was chosen to imitate modulation patterns common to pinniped vocalizations. An ad hoc analysis of pinniped underwater and aerial vocalizations, including barks, growls, and pup attraction calls of phocids and otariids, was conducted to determine this modulation frequency.

Absolute detection thresholds for AM signals were well predicted by the audiogram for the California sea lion but not for the harbor seal. A priori threshold predictions were made based on a linear interpolation of the audiogram at the carrier frequency. All observed thresholds were within 5 dB of the predicted value for the California sea lion. Thresholds observed for the harbor seal varied less than expected with changes in the carrier frequency. Although the predicted thresholds for this subject and this stimulus varied by 12 dB across carrier frequencies, the measured thresholds for all four carriers were within 5 dB of one another, possibly indicating that, for this animal, the characteristics of the envelope, which remain constant across stimuli, were more critical to detection than the frequency of the carrier signal. Further work is needed to determine if this is a trait that varies by species, by individual, or both.

3.3 Harmonic Stimuli

Harmonic stimuli were created by summing four narrowband linear FM upsweeps: the fundamental frequency and its first three linear multiples. The FM bandwidth for all harmonic components was set to one-fourth octave of the fundamental frequency. Fundamental frequencies of 500 and 2,000 Hz were used to generate two distinct signals. Target harmonic sound pressure levels decreased relative to the fundamental in the projected signal such that the first harmonic was −3 dB relative to the fundamental, the second −6 dB, and the third −12 dB. However, reverberant conditions within the test pool resulted in distorted relative levels at the receiver. Because of this, the levels of all harmonics were recorded immediately before all experimental sessions and predictions were made based on the relative levels for that session.

Absolute detection thresholds for harmonic stimuli were lower than those predicted for both species and both fundamental frequencies. A priori predictions were made based on the minimum threshold for any of the individual harmonics contained within the signal. Signal levels were calibrated based on the sound pressure level of the fundamental, and daily threshold predictions were adjusted based on the observed harmonic levels relative to the fundamental. Five sessions, each containing five hit-to-miss transitions, were obtained for each animal for fundamental frequencies of 500 and 2,000 Hz. For all five sessions, at both frequencies, for both animals, observed thresholds were lower than predicted, as shown in Fig. 21.1. The difference between threshold predictions and observations ranged from 1 to 12 dB. Larger differences were observed for the harbor seal at both fundamental frequencies, and the 2,000-Hz fundamental stimuli showed larger differences in both species.

These results are interesting relative not only to concerns about ocean noise but also to how the auditory system processes complex signal features, including multiple harmonics. The fact that threshold predictions based on what should be the perceptually loudest harmonic component are too high suggests that, in quiet conditions, detection of harmonic stimuli involves the comparison of information across multiple-frequency channels. That is, the fact that detection occurs at sound pressure levels where all of the individual harmonic components should be undetectable implies that information is being integrated across critical bands at levels below the narrowband thresholds for the individual frequency components to determine the detectability of a signal. Furthermore, this result implies that even at these

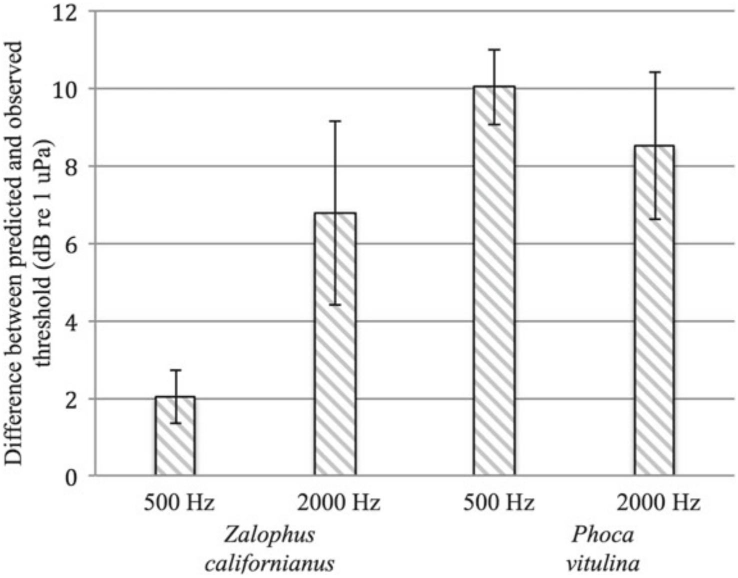

Fig. 21.1 Differences ±95% confidence intervals between average predicted and observed thresholds for harmonic stimuli with fundamental frequencies of 500 and 2,000 Hz for a California sea lion and a harbor seal

subthreshold levels, enough stimulation occurs at multiple regions along the basilar membrane to pass information along to higher order processing regions.

4 Future Directions

An expanded understanding of absolute detection thresholds is only one piece of the puzzle needed to set appropriate noise-exposure criteria for marine mammals. Future work should focus on establishing which parameters most influence masked detection thresholds for complex signals. Current masking models rely on critical ratios observed for pure tones in flat-spectrum noise (Dooling et al. 2009). However, it is known that the presence of certain spectral and temporal features, particularly AM that is coherent across multiple auditory filters (comodulation), can strongly influence a listener's ability to detect signals in noise (Hall et al. 1984; Branstetter and Finneran 2008). Furthermore, depending on how the information contained within a signal is being utilized, a signal level adequate for simple detection is not always sufficient for functional hearing. Understanding how signals are used by listeners and how thresholds vary for more difficult perceptual tasks, such as auditory discrimination and recognition, must be developed. Only by generating a more complete model of auditory processing of complex signals can we hope to set appropriate noise-exposure criteria that ensure that anthropogenic noise is not interfering with hearing processes critical to the long-term health of marine mammal species.

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Chapter 22
Offshore Dredger Sounds: Source Levels, Sound Maps, and Risk Assessment

Christ A.F. de Jong, Michael A. Ainslie, Floor Heinis, and Jeroen Janmaat

Abstract The underwater sound produced during construction of the Port of Rotterdam harbor extension (Maasvlakte 2) was measured, with emphasis on the contribution of the trailing suction hopper dredgers during their various activities: dredging, transport, and discharge of sediment. Measured source levels of the dredgers, estimated source levels of other shipping, and time-dependent position data from a vessel-tracking system were used as input for a propagation model to generate dynamic sound maps. Various scenarios were studied to assess the risk of possible effects of the sound from dredging activities on marine fauna, specifically on porpoises, seals, and fish.

Keywords Shipping • Marine fauna • Threshold shift

1 Introduction

The Port of Rotterdam is expanding to meet the growing demand to accommodate large cargo vessels. The construction of Maasvlakte 2 (MV2), an area of ~20 km^2 reclaimed from the North Sea, started in 2008. One of the licensing conditions was the monitoring of the underwater sound produced during its construction. During a measurement campaign in 2008, ambient-sound measurements were performed in the absence of dredging (Dreschler et al. 2009). In 2009, measurements were made of the sound of the trailing suction hopper dredgers (TSHDs) and of the ambient sound while MV2 dredging activities were underway (de Jong et al. 2010). The risk of possible effects on the marine fauna of underwater sound associated with the dredging was considered (Ainslie et al. 2012).

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2 Ambient-Sound Measurements

Measurements of ambient sound before construction of MV2 were conducted over a period of 5.5 consecutive days in September 2008 at a fixed location <5 km from the area where the sand was to be dredged and from the future MV2. Two hydrophones were deployed from a small boat 2 and 7 m above the seabed in ~20 m water depth. A 6-s sample was recorded every minute.

To eliminate the practical problems associated with recording underwater sound from a boat during an extended time period, the Netherlands Organization for Applied Scientific Research (TNO) developed the Shallow water Extendible Stand-alone Acoustic Measuring System (SESAME), which was deployed during a representative week of MV2 construction in September–October 2009, with seven TSHDs active. SESAME was positioned on the seafloor ~2 km east of the measurement location in the 2008 campaign to mitigate the risk of damage to the system by fishing vessels. SESAME recorded the signals of two hydrophones 2 and 7 m above the seabed.

In both measurement campaigns, information on all automatic identification system (AIS)-logged shipping in the vicinity of the MV2 area, including the active dredgers, was used to investigate the correlation between shipping activity and ambient-sound levels. Weather conditions, such as wind speed, wind direction, and rain rate, were monitored.

The acoustic data collected using the hydrophones were converted into third-octave band sound pressure level (SPL) spectra for each recorded 6-s sample. The statistics of the third-octave band spectra are shown in Fig. 22.1.

There was a strong correlation between the SPL and the distance to the dredgers. The dredgers in transit between the dredging area and the MV2 construction site contributed most to the measured underwater sound as recorded by SESAME in 2009. The dredgers occasionally sailed very close to SESAME so that the variations in the ambient sound measured in 2009 were much higher than the variations measured in 2008.

At frequencies above 10 kHz, sound caused by the wind, for example, as a result of breaking waves, was a significant component of the ambient sound. In the frequency range between 100 Hz and 10 kHz, a negative correlation was found between wind speed and ambient sound, probably as result of an increase in propagation loss by scattering and absorption at the rough water surface. The dip in the 2009 curves at 3 kHz (Fig. 22.1) was most likely caused by the nighttime dispersal of large numbers of small fish with a swim bladder (de Jong et al. 2010). A similar bladder resonance effect was observed in the Baltic Sea by Klusek and Lisimenka (2007). This dip did not affect the broadband SPL.

The local effects observed in the measurements at a single position do not provide sufficient information to draw conclusions about possible additional effects of the dredging activities on the overall underwater ambient sound in the MV2 area. Therefore, it was decided to apply a propagation model to generate ambient-sound maps for the area based on measured source levels for the TSHDs, estimated source levels for other shipping, and information from a vessel-tracking system.

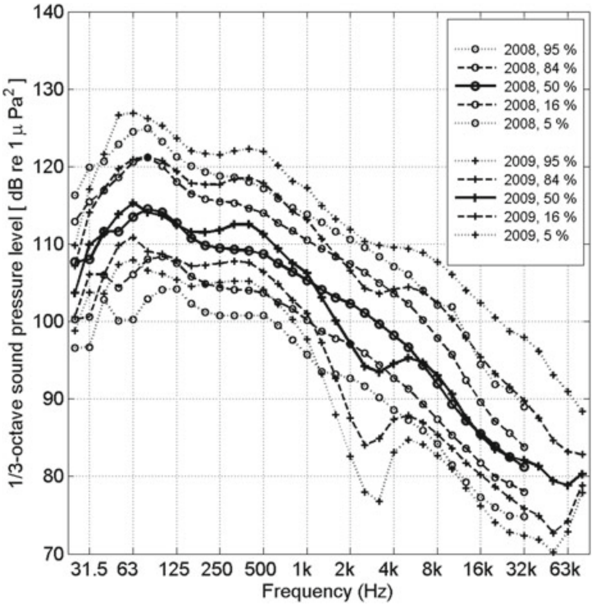

Fig. 22.1 Statistic *N* percent exceedance levels of the measured third-octave sound pressure level spectra at a fixed station in the Maasvlakte 2 (MV2) area in 2008 and 2009

3 TSHD Underwater Sound Measurements and Source Levels

There are no specific national or international standards for measuring the radiated sound of dredgers or of other ships operating in shallow water. TNO proposed a new measurement procedure and analysis method (de Jong et al. 2010). A similar procedure was adopted by Robinson et al. (2011).

The radiated sound of individual TSHDs, linked to the various phases of the dredging cycle, was recorded by two hydrophones suspended from a small measurement vessel, nominally at 6 and 12 m below the sea surface. Measurements were made with the TSHD passing the hydrophones on a straight track (during dredging and transiting) or with the measurement vessel positioned at various distances from the static TSHD (when discharging sand). Measurement distances ranged from 40 to 500 m in water depths varying between 4 m in the discharge area (hydrophone at 1 m depth) and 36 m in the dredging area.

An "image source" model (Urick 1983) was used to estimate the propagation loss (PL) between the acoustic center of the dredger and the various hydrophone positions. The acoustic center was chosen at the location of the GPS antenna on the vessel and at 4 m below the water surface. The water depth and sound speed in water and the sediment were assumed to be uniform. The sediment was modeled as a semi-infinite fluid space characterized by a compressional wave speed, density, and loss factor, with the sediment properties for "medium sand" taken from Ainslie (2010). The water-air interface was assumed to be flat and fully reflecting for consistency with a worst-case (highest shipping sound) scenario. The absorption coefficient in seawater was estimated using Urick's modification of Thorp's formula (Urick 1983). Narrowband calculations were carried out for 11 logarithmically spaced frequency lines within each third-octave band. The resulting PL per band was determined by averaging the individual propagation factors (Ainslie 2010). Comparison with the calculation results from the OASES code for modeling seismoacoustic propagation in waveguides (http://acoustics.mit.edu/faculty/henrik/oases.html; accessed 25 June 2013) showed approximately equal results for frequencies of 160 Hz and above. Below 160 Hz, the image source model underestimated the PL by 3–6 dB.

The monopole source level (MSL) of an underwater sound source is a measure of the amount of sound radiated to the far field of that source (Ainslie 2010, Section 8.3.1.1). Third-octave band MSL spectra of the TSHDs during their various activities are estimated by adding the calculated PL to the measured SPL for the various measurement distances. The various MSL spectrum estimations show a spread of the order of ±5 dB around their (dB) average.

In practice, reflections at the water surface have a large impact on the sound radiated by ships, often referred to as Lloyd's mirror effect. When comparing published ship "source levels," one needs to be aware of the assumed depth of the acoustic center, experimental procedures, and environmental parameters as well as differences in reference distances, units, and bandwidths that arise due to the absence of standard measurement or reporting procedures. The actual depth of the acoustic source mechanisms will differ per ship and per activity. A dipole source level (DSL) includes the contribution of the surface image and is therefore approximately independent of the assumed source depth. de Jong et al. (2010) reported 74 DSLs from 7 TSHDs (with hopper volumes between 3,000 and 20,000 m^3 and a total installed power between 5 and 30 MW) during transit and dredging and discharge of sediment (rainbowing, pumping shore, and bottom discharge).

The TSHDs produced the most sound during transit between the borrow and discharge areas (at speeds between 9 and 17 kn). During sand dredging (at 1–2 kn), the maximum source levels in most third-octave bands were only a few decibels lower. During pumping ashore and rainbowing, the maximum source level at frequencies between 500 Hz and 10 kHz was comparable with that of a vessel dredging sand, but it was substantially lower at frequencies outside this range. The lowest source levels were measured during the bottom discharging of sand at frequencies above 1 kHz and at frequencies of 500 Hz and less during rainbowing. In all probability, the production of underwater sound by dredgers is primarily caused by cavitation linked to the propellers and bow thrusters.

4 Sound Maps

In contrast with local ambient-sound measurements, acoustic modeling can provide an overview of underwater ambient-sound levels in a wide area. TNO applied its AQUARIUS sound-propagation model, an adapted implementation of the theory described by Weston (1971, 1976), to produce dynamic sound maps for the MV2 area during the dredging activities on 29 September 2009 (a movie with 1 image/

min). Locations of the ships were taken with the AISs. The maximum measured third-octave band MSL spectrum was selected for the individual TSHDs during the various activities and a statistically averaged MSL spectrum (Wales and Heitmeyer 2002) for the other ships in the area, taking into account only the ships traveling at a speed exceeding 3 m/s. Calculations were performed on the third-octave band spectra. The broadband SPL was obtained by integrating the results over the entire frequency range, applying a weighting for animal sensitivity where appropriate. Each calculated map was a snapshot of the broadband SPL distribution 1 m below the sea surface or 1 m above the seafloor in a 15- × 15-km^2 area around MV2 at intervals of 1 min during 24 h (1,440 maps/receiver depth). The snapshots were summed and multiplied by the 1-min interval duration to obtain the SEL accumulated over 24 h, a total sound dose received in that period at each location. Results for the unweighted broadband SEL are shown in Fig. 22.2. Due to the snapshot approach, a track of a ship appears as a series of dots. The contribution of the TSHD activities to the 24-h exposure can be read off by comparing the left-hand images (regular shipping only) with the right-hand images (regular shipping + dredgers).

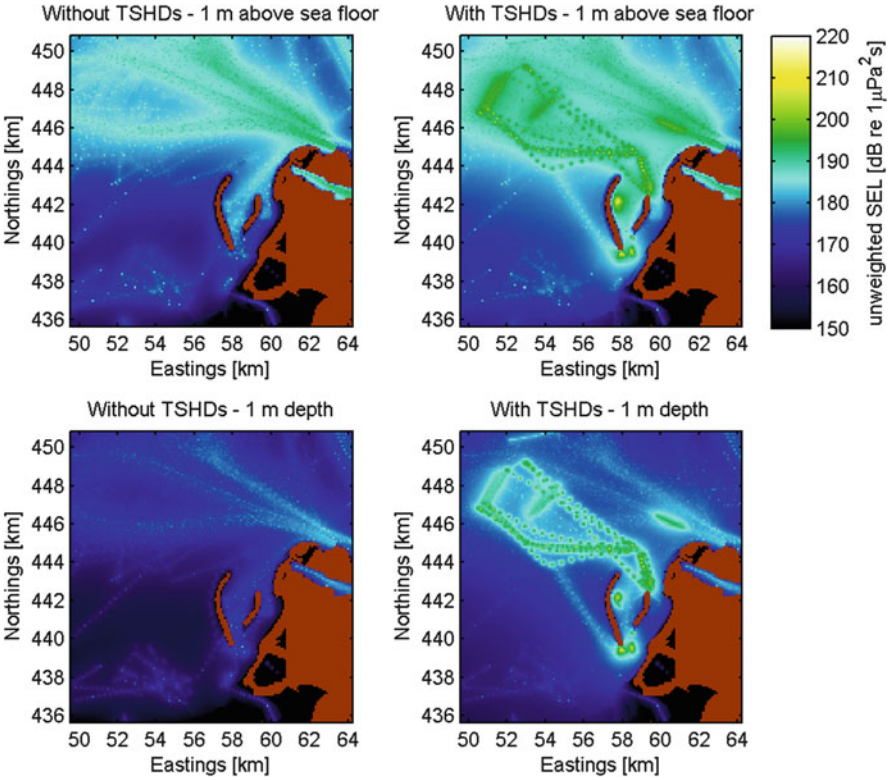

Fig. 22.2 Sound maps of the 24-h cumulative unweighted broadband sound exposure level (SEL) generated by regular shipping (*left*) and regular shipping plus trailing suction hopper dredgers (TSHDs; *right*) at a depth of 1 m above the seabed (*top*) and 1 m below the sea surface (*bottom*). *Brown* areas indicate the land of the existing Maasvlakte and the new contours of MV2 at the time of the measurements

5 Risk Assessment

A risk assessment framework approach (Boyd et al. 2008; WODA 2013) was adopted to quantify the possible effects of the MV2 dredging activities on harbor porpoises (*Phocoena phocoena*), harbor seals (*Phoca vitulina*), and various fish species. An important knowledge gap for environmental impact studies is the lack of knowledge of thresholds for behavioral effects and injury in general. This lack of knowledge was the main reason for choosing to focus on the onset of physiological effects as a proxy for other effects. As suggested by Southall et al. (2007), it was assumed that the magnitude of the effect increases linearly with the SEL ("equal-energy hypothesis"). The risk assessment was made on the basis of the cumulative SEL (in dB re 1 μPa^2 ·s) to which animals could have been exposed on a representative day (24 h) in which seven dredgers were active.

The main risk considered for affecting the marine mammals is that of a temporary rise in the hearing threshold known as a temporary threshold shift (TTS). TTS onset, defined as a rise in the hearing threshold by 6 dB (measured within 4 min after exposure at any frequency in the hearing range), is assumed to occur when the cumulative SEL exceeds an animal-specific threshold value. In this study, we adopted the threshold values for "M-weighted" SEL corresponding to "nonpulses" recommended by Southall et al. (2007): 183 dB for seals and 195 dB for porpoises. Recently, Kastelein et al. (2012a, b, 2013) published the results of studies in which the TTS was measured in a harbor porpoise and two harbor seals after exposure to continuous sound in the 4-kHz octave band. These measurements show TTS onset at 4 kHz at much lower unweighted SEL values (163–172 dB for harbor porpoises and 173–183 dB for harbor seals) than indicated by the Southall et al. (2007) threshold. They also indicate that a single SEL threshold value is probably insufficient to quantify the risk of TTS onset.

The impact on fish was quantified in relation to the cumulative SEL thresholds associated with auditory and nonauditory tissue damage due to pile-driving sound, proposed as interim criteria by the US Fish Hydroacoustic Working Group (Oestman et al. 2009): 183 dB for small fish (<2 g) and 187 dB for larger fish. Recent studies (Bolle et al. 2012; Halvorsen et al. 2012a, b) showed that fish and fish larvae are probably much less susceptible to impulsive sound than indicated by these interim criteria. They observed no onset of injury below a cumulative SEL of ~207 dB.

The 24-h maps (Fig. 22.2) show the cumulative SEL in a "'worst–case" scenario in which animals stay at the same position for 24 h. For regular shipping, the spatial average of the unweighted SEL in the maps for 1 m above the seafloor is 176 ± 16 dB (arithmetic mean of the SEL values ±SD). With the dredgers active, this increases to 180 ± 16 dB. At 1 m below the sea surface, the spatially averaged SELs are 165 and 173 dB, respectively.

In reality, marine animals in natural conditions never stay at the same location for such a long time. Using the individual snapshot sound maps for the same 24 h, the cumulative SEL was calculated for animals swimming from south to north along straight lines between 50 and 57 km east. They swim 1 m above the seabed at a constant speed of 1.7 m/s without a behavioral response to the ships, starting from

15 different starting positions at 15-min intervals. The 1,440 animals crossing the area are exposed to an unweighted SEL of 171 ± 3 dB due to regular shipping only and 175 ± 3 dB due to regular shipping plus dredgers. When crossing the area repeatedly (8.9 times in 24 h), the cumulative SEL is ~10 dB higher.

It can be concluded from the calculations that the average daily sound exposure of marine animals in the area was increased by ~4 dB due to the dredging activities for MV2. Because of the large uncertainty associated with dose–response relationships for the effects of underwater sound on marine life, it is not possible to quantify the significance of such an increase.

Assessment of the risks associated with the impact of radiated sound from ships on marine fauna is hampered by the current lack of information on dose–response relationships. There is a strong need for experimental data of the behavioral response, TTS, and injury (whether for seal, porpoise, or fish) resulting from exposure to continuous broadband sound in a frequency range relevant to the radiated sound from ships and dredgers.

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Chapter 23
Effects of Offshore Wind Farms on the Early Life Stages of *Dicentrarchus labrax*

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Kris Hostens, Magda Vincx, and Steven Degraer

Abstract Anthropogenically generated underwater noise in the marine environment is ubiquitous, comprising both intense impulse and continuous noise. The installation of offshore wind farms across the North Sea has triggered a range of ecological questions regarding the impact of anthropogenically produced underwater noise on marine wildlife. Our interest is on the impact on the "passive drifters," i.e., the early life stages of fish that form the basis of fish populations and are an important prey for pelagic predators. This study deals with the impact of pile driving and operational noise generated at offshore wind farms on *Dicentrarchus labrax* (sea bass) larvae.

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Keywords *Dicentrarchus labrax* • Pile driving • Continuous noise • Offshore wind farms

1 Introduction

Offshore wind farms are being installed across the North Sea, including the Belgian part in which a concession zone is designed for the production of renewable energy and will host seven farms (Fig. 23.1). Three types of foundations have already been used, i.e., gravity-based foundations, monopiles, and jackets requiring four pin piles. The latter two are driven into the seabed and have a comparable single-strike sound exposure level (SEL_{ss}) that varies between 145 and 168 dB re 1 $\mu Pa^2 \cdot s$ at 750 m but have a different number of strikes and amount of piling time (Norro et al. 2013).

The construction phase of offshore wind farms raises questions about the possible impact it might have on the marine wildlife. Pile driving generates low- and midfrequency impulsive noise. At the moment, a growing group of scientists is conducting research on marine mammals and fishes looking for the possible effects on mortality, external and internal tissue damage, temporary and permanent hearing loss, physiological stress, and disturbance of natural behavior and distribution (Popper and Hastings 2009). The differences in species-specific hearing capabilities as well as vulnerability between fish species, fish sizes, and life stages complicate this bioacoustics research.

Research is moving toward defining the biological impact related to the SEL_{ss}, the cumulative SEL (SEL_{cum}), and the number of impulses (Halvorsen et al. 2012). A SEL_{cum} of 210 dB re 1 $\mu Pa^2 \cdot s$ was defined as the threshold for the onset of injury for chinook salmon, but such levels only occur close to the piling source (Casper et al. 2012; Halvorsen et al. 2012). Practically no knowledge exists on the sound levels that cause mortality or injury to fish eggs, larvae, and fry. Given that their transport is mainly current based (Bolle et al. 2005), they are condemned to endure any underwater noise present in the water column. Accordingly, it is very important to determine the threshold sound levels causing any disturbance.

The ecological importance of fish eggs, larvae, and fry to maintain a healthy population size and their nutritional value in the pelagic food web only emphasizes the urgent need to establish these levels (Bos et al. 2009). Prins et al. (2009) made a first assumption about the impact of pile driving on fish eggs and larvae: “100% mortality of fish eggs and larvae in a radius of 1 km around the piling source.” This assumption was based on very little information (current patterns, dispersal, and ecological value). After the laboratory experiment in Bolle et al. (2012), a revision of this assumption was recommended. However, no field experiments have yet validated the laboratory experiments or the assumption, exposing a crucial gap in this research area that needs urgent attention.

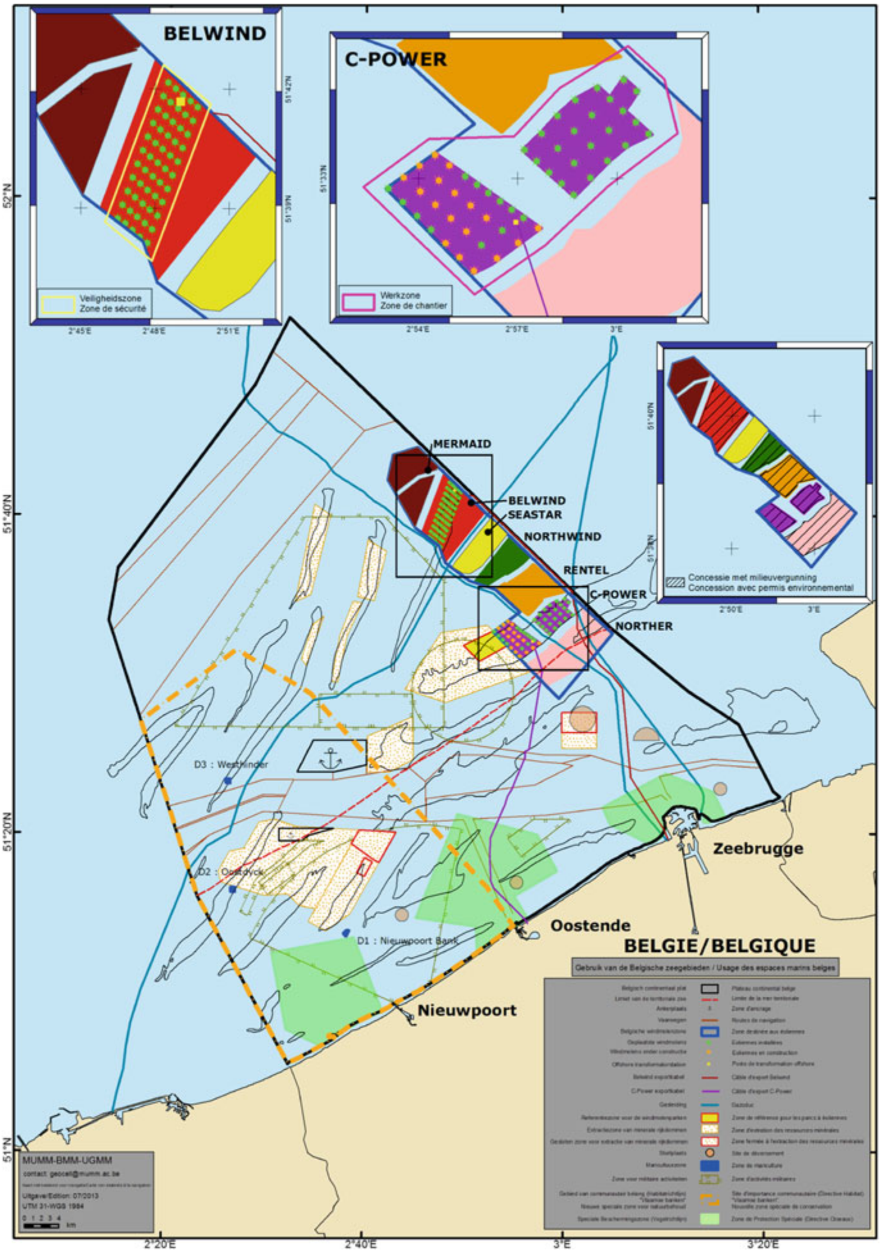

Fig. 23.1 Belgian part of the North Sea with the offshore wind farm area. At the moment, C-power at the Thornton Bank, Belwind at the Bligh Bank, and Northwind at the Lodewijck Bank are installed or under construction. Reproduced from Vigin et al. (2013) with permission from the Management Unit of the North Sea Mathematical Models (MUMM)

The introduction of long-term continuous noise into the marine environment receives far less attention even though it is also a concern in aquaculture. The operational phase of the offshore wind farms will cause higher background sound pressure levels for the next 20 year (Norro et al. 2011). At the offshore wind farm on the Bligh Bank (Belgium), wind turbines on monopiles elevate the background underwater sound pressure level ~20 dB re 1 μPa (Norro et al. 2010). It is suggested that an increase in the background noise can interfere with the foraging behavior and communication of fish and induce stress in fish (Hastings and Popper 2005; Wahlberg and Westerberg 2005; Thomsen et al. 2006; Mueller-Blenkle et al. 2010). However, the impact on the early life stages of fish remains relatively unknown.

2 Objectives

A multidisciplinary study combining biology, acoustics, physiology, and biochemistry was designed to examine the impact of the construction and exploitation of offshore wind farms on the early life stages (eggs, larvae, and fry) of fish in Belgian waters. *Dicentrarchus labrax* (European sea bass) was chosen as the model species for round fish. The first work package (WP1) of the project dealt with the impact of pile-driving noise and tackled the impact assessment from different angles. (1) The worst-case scenario (close range) was analyzed onboard the piling platform Neptune (Northwind NV and its contractor GeoSea). (2) The impact at 500 m was examined onboard a research vessel. (3) In parallel, noise-exposure experiments were carried out under controlled conditions in the laboratory.

The second work package (WP2) of the project dealt with the chronic effects of operational noise on the development of fish eggs, larvae, and fry. These experiments were carried out under controlled conditions in the laboratory.

3 Target Species

Dicentrarchus labrax is a commercially important round fish species in fisheries as well as in the aquaculture industry. *Dicentrarchus labrax* is a well-studied species, in particular the larval growth, development, and skeletal formation (Zouiten et al. 2011). In addition, the year-round availability of the eggs, larvae, and fry in the Ecloserie Marine de Gravelines (France) is rather exceptional for a marine fish species. Consequently, *Dicentrarchus labrax* is frequently used in experiments and was used here as a model species for round physoclist fish (Pickett and Pawson 1994).

4 Work Packages

4.1 WP1

The general aim of the WP1 was to assess the impact of pile driving on eggs, larvae, and fry of *Dicentrarchus labrax*. (1) An experiment onboard the piling platform Neptune (Northwind NV and its contractor GeoSea) 43 m from the sound source analyzed the worst-case scenario (Fig. 23.2). *D. labrax* was exposed to pile-driving noise for a complete piling event of one monopile at 2.5 m depth in 500-ml vials, and the results were compared with a control group on land with no handling stress and a control group that underwent the same handling as the exposed group. Simultaneously, the sound pressure and particle velocity were measured. Immediate and delayed mortality were observed during and after the experiment. Physiological stress was determined by measuring whole body cortisol, analyzed with a cortisol

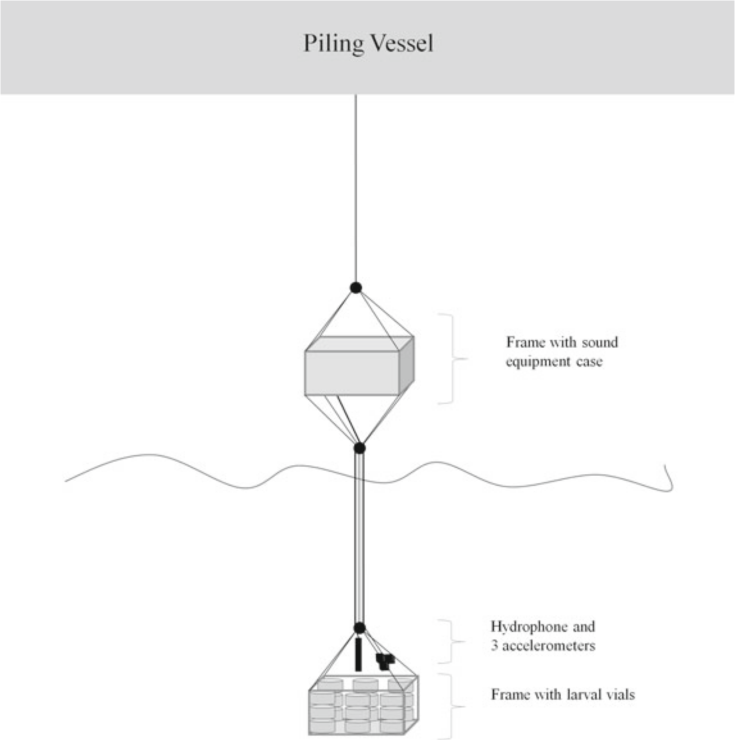

Fig. 23.2 Experimental setup to conduct the experiment on board the piling platform. The structure exists of one frame above the sea surface holding the sound equipment case with recorder and amplifier and a second frame 4 m in the sea containing the 500-mL vials of *Dicentrarchus labrax*. The hydrophone and 3-axis accelerometers are mounted just above the larval frame in the sea and are connected to the amplifier in the sound equipment case

radioimmunoassay kit, and calculating the respiration as determined by the difference in oxygen level in the vials at the start and end of the experiment. Ten percent of the surviving larvae were stored in 7% formaldehyde for histological analysis and the rest were transported back to the laboratory for further monitoring of their development.

(2) The impact at 500 m was examined onboard a research vessel and had the same experimental setup and approach as the experiment onboard the piling vessel.

(3) In parallel, noise-exposure experiments were carried out under controlled conditions in the laboratory and had the same experimental setup as the field experiments. A SIG Sparker Electrode submerged in a 400,00-l reservoir shot 3,000 V at 300 J/s and generated low-frequency impulsive noise, mimicking the sound pressure levels of pile-driving noise between 70 and 500 m from the piling source. The advantage of this experiment is the considerably reduced handling stress compared with the field experiments. The results were compared.

4.2 WP2

Chronic effects were examined during and after exposure of *D. labrax* eggs and larvae to the playback of the operational noise recordings for 1 month. The experimental design consisted of four groups: (1) a silent group; (2) a group only exposed during embryonic development; (3) a group only exposed during larval development; and (4) a group continuously exposed during both embryonic and larval development. Embryonic development, hatching percentage, time of hatching, and diameter of the yolk sac gave information about their viability and fitness. Larval development, yolk sac resorption, growth, symmetry, skeletal development, and chronic stress (Hsp70) were monitored.

5 Output

This paper presents the design of a doctoral thesis and no results are provided. Results that were obtained in WP1 and WP2 will serve several purposes. The US Fisheries Hydroacoustic Working Group formulated interim criteria for the maximum noise levels that fish could be exposed to without causing nonauditory tissue damage. The interim criterion for maximum $\mathrm{SEL}_{\mathrm{cum}}$ for fish less than 2 g was set at 183 dB re 1 $\mu\mathrm{Pa}^2\cdot\mathrm{s}$. The results of WP1 can contribute to the reexamination of these interim criteria. In addition, the experiment onboard the piling vessel in WP1 will allow validating the assumptions of Prins et al. (2009) and the results of Bolle et al. (2012; cf. supra). WP1 and WP2 deal with both underwater noise indicators: (1) low- and midfrequency impulsive noise and (2) ambient noise as determined by the European Commission Directive 2008/56/EC in the Marine Strategy Framework Directive-Good Environmental Status (MSFD-GES; van der Graaf et al. 2012). These data are relevant to a scientifically based implementation of the MSFD-GES.

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Chapter 24
The European Marine Strategy: Noise Monitoring in European Marine Waters from 2014

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Abstract The European Marine Strategy Framework Directive requires European member states to develop strategies for their marine waters leading to programs of measures that achieve or maintain good environmental status (GES) in all European seas by 2020. An essential step toward reaching GES is the establishment of monitoring programs, enabling the state of marine waters to be assessed on a regular basis. A register for impulsive noise-generating activities would enable assessment of their cumulative impacts on wide temporal and spatial scales; monitoring of ambient noise would provide essential insight into current levels and any trend in European waters.

Keywords Marine Strategy Framework • Good environmental status • Environmental descriptors • Indicators • Monitoring

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1 Introduction to the Marine Strategy Framework Directive

1.1 Overall Goal of the Marine Strategy Framework Directive

In 2008, the European Parliament and the Council of the European Union (EU) adopted the Marine Strategy Framework Directive (MSFD; European Commission 2008). The overall objective of the MSFD is to achieve or maintain good environmental status (GES) of the EU's marine waters by 2020. The MSFD prescribes an ecosystem-based and integrated approach to the management of all human activities that have the potential for impact on the marine environment; there should be a regional approach to implementation, and therefore the MSFD has defined European marine regions.

1.2 Implementation of the MSFD

The MSFD requires member states to develop strategies for their marine waters, including programs of measures that will achieve or maintain GES by 2020. Marine strategies include an initial assessment, a description of GES for the 11 descriptors listed in Annex I, and establishment of environmental targets and associated indicators and needed to be defined by 2012. Programs of the measures need to be defined by 2015 and implemented by 2016. As an essential step toward reaching GES, member states should have established monitoring programs by 2014, enabling the state of their marine waters to be assessed on a regular basis.

1.3 The MSFD and Underwater Sound

Along with introducing the ecosystem approach and integrated and regional management, the implementation of the MSFD requires that emerging pressures such as marine litter, underwater noise, or nonindigenous species and emerging human activities such as offshore energy, deep seabed exploration, and marine biotechnology be addressed in an integrated approach.

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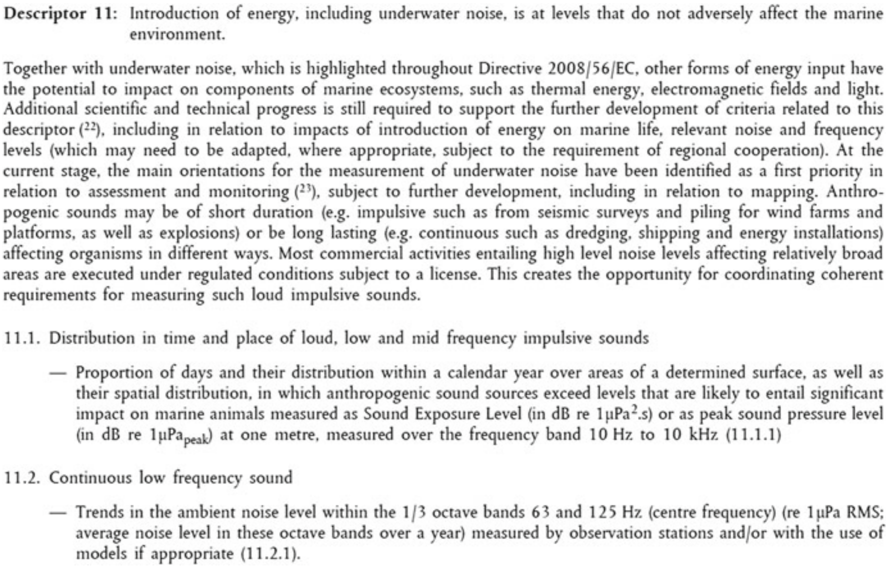
In Article 3 of the MSFD, a definition for pollution was provided. In this definition, underwater noise is explicitly mentioned as a possible form of pollution (".... the direct or indirect introduction into the marine environment, as a result of human activity, of substances or energy, including human-induced marine underwater noise, which results or is likely to result in deleterious effects ...."); energy, including underwater noise, is also listed as one of the descriptors of GES (Descriptor 11), implying that member states should ensure that "introduction of energy, including underwater noise, is at levels that do not adversely affect the marine environment."

1.4 Criteria and Methodological Standards

When providing further direction for monitoring programs and in line with the recommendations of Tasker et al. (2010), in September 2010, the European Commission (EC) decided that with respect to energy, measurement of underwater noise should have first priority in relation to assessment and monitoring (EC Decision 2010/477/EU on criteria and methodological standards on GES of marine waters). The need for further development of criteria, including in relation to the impact of the introduction of energy on marine life, was identified, but indicators for underwater noise were defined as priority: one indicator (11.1.1) on "low- and midfrequency impulsive sounds" and one indicator (11.2.1) on "continuous low-frequency sound" (ambient noise). Figure 24.1 shows the extract of the EC decision specifically for the indicators of Descriptor 11.



Descriptor 11: Introduction of energy, including underwater noise, is at levels that do not adversely affect the marine environment.

Together with underwater noise, which is highlighted throughout Directive 2008/56/EC, other forms of energy input have the potential to impact on components of marine ecosystems, such as thermal energy, electromagnetic fields and light. Additional scientific and technical progress is still required to support the further development of criteria related to this descriptor (22), including in relation to impacts of introduction of energy on marine life, relevant noise and frequency levels (which may need to be adapted, where appropriate, subject to the requirement of regional cooperation). At the current stage, the main orientations for the measurement of underwater noise have been identified as a first priority in relation to assessment and monitoring (23), subject to further development, including in relation to mapping. Anthropogenic sounds may be of short duration (e.g. impulsive such as from seismic surveys and piling for wind farms and platforms, as well as explosions) or be long lasting (e.g. continuous such as dredging, shipping and energy installations) affecting organisms in different ways. Most commercial activities entailing high level noise levels affecting relatively broad areas are executed under regulated conditions subject to a license. This creates the opportunity for coordinating coherent requirements for measuring such loud impulsive sounds.

11.1. Distribution in time and place of loud, low and mid frequency impulsive sounds

— Proportion of days and their distribution within a calendar year over areas of a determined surface, as well as their spatial distribution, in which anthropogenic sound sources exceed levels that are likely to entail significant impact on marine animals measured as Sound Exposure Level (in dB re $1\mu Pa^2.s$) or as peak sound pressure level (in dB re $1\mu Pa_{peak}$) at one metre, measured over the frequency band 10 Hz to 10 kHz (11.1.1)

11.2. Continuous low frequency sound

— Trends in the ambient noise level within the 1/3 octave bands 63 and 125 Hz (centre frequency) (re 1μPa RMS; average noise level in these octave bands over a year) measured by observation stations and/or with the use of models if appropriate (11.2.1).

Fig. 24.1 Extract of the indicators for Descriptor 11 (Noise/Energy) from European Commission Decision 2010/477/EU

The two indicators are very different in nature; in both cases, it is not known what GES would actually be, primarily because there has been very little work on the ecosystem-scale effects of underwater noise. For a limited number of species, the effects are known on individual and small-group scales but not at greater (e.g., population) scales as required by the MSFD. Consequently, the first stage of the implementation of monitoring schemes is to establish a baseline of current conditions.

In 2010, the EC also decided that an expert working group that would further develop these indicators and provide guidance to member states on the monitoring of underwater sound was needed. The Technical Subgroup Noise (TSG Noise) was established in 2011 and consisted of appointed experts representing governments, academia, nongovernmental organizations, and commercial parties. TSG Noise has since provided two advice documents (van der Graaf et al. 2012; Dekeling et al. 2014). This paper reflects the main recommendations of TSG Noise and the implications for monitoring programs in European waters.

2 Monitoring of Impulsive Noise

2.1 Aim/Effect Addressed by Impulsive Noise Indicator

High-amplitude, low-frequency (<1 kHz), and midfrequency (between 1 and 10 kHz) impulsive sounds have caused concern because of the possible impacts on marine mammals and fishes. Relevant sounds include those from offshore construction (such as pile driving), the use of air guns during seismic surveys, acoustic deterrents, various types of sonar, and explosions.

Because the MSFD addresses the ecosystem rather than individual animals or species, the indicator for impulsive noise aims to address the cumulative impact of all these activities within a region rather than that of individual projects or programs; the effects of localized individual activities are therefore not covered, and this indicator on its own is not intended nor is it sufficient to manage individual projects. The effects of these individual projects should be covered by other national or EU legislation, and environmental impact assessments can be used to assess and, where necessary, limit the environmental impacts.

The impact that is addressed by Indicator 11.1.1 is “considerable” displacement. This means displacement of a significant proportion of individuals for a time period and spatial scale relevant to the objectives of the MSFD. The indicator addresses the cumulative impact of sound-generating activities and possible associated displacement within a region rather than localized displacement related to individual projects (van der Graaf et al. 2012).

Earlier approaches toward management of underwater sound made a distinction between sounds with an explicitly impulsive character (i.e., a transient signal with a short rise time) and more continuous sounds because of the resulting physiological effects like auditory fatigue or acoustic trauma, e.g., separating “pulse” and "nonpulse"(Southall et al. 2007). In the approach of the EU, some sounds that do not have this explicitly impulsive character but are still characterized by short duration (whether or not repeated) fall in the description of impulsive; see van der Graaf et al. (2012) for a further detailed description.

The choice to address "displacement" does not preclude individual EU member states from addressing other effects (e.g., other behavioral or physiological effects) if under the MSFD they consider these effects to be adverse effects on the marine environment.

The initial purpose of this indicator is to assess the cumulative pressure on the environment by making available an overview of all loud impulsive low- and mid-frequency sound sources through the year and throughout regional seas. This will enable member states to get an overview of the overall pressure on the environment from these sources, which has not been achieved previously.

2.2 *Description of Sound Sources to Be Registered, including Their Source Levels*

Seismic surveying, pile driving, explosions, sonar operation at relevant frequencies, and the use of some acoustic deterrent devices are the most important sound-producing activities that should be considered for monitoring. Most of the activities generating such sounds are executed under regulated conditions, often subject to a license, and therefore the information needed for monitoring is often available (from an environmental impact assessment or another form of reporting activities). This creates the opportunity for setting up a register of sources of these impulsive sounds. The purpose of the register would be to record the information relevant to quantifying the region of time and space in which a significant impact resulting from the use of the impulsive sources may occur.

The MSFD provides an exemption for "activities the sole purpose of which is defence or national security." TSG Noise has recommended that information on all military sources be included. The aim is to address cumulative effects of all impulsive noise sources so data on these sources and their associated activities would be needed. This implies that data on these activities should be included in the register on a voluntary basis because it is understood that this is a national policy issue.

Minimum noise thresholds have been defined for low- and midfrequency sources as a basis for including sources in the register. For impact pile drivers and multiple explosions, no minimum threshold should be used and all pile-driving activities and all use of multiple explosions at a single site should be registered. For sonar, air guns, acoustic deterrents, and single explosions, minimum thresholds should be used for inclusion in the registers (Dekeling et al. 2014).

There are additional sources of possible concern (e.g., boomers, sparkers, scientific echo sounders). The thresholds that were derived and recommended will ensure that all sources that have a potential for a significant population-level effect will be included in the register. The use of these relatively low thresholds will result in sources being registered that may actually have a relatively low potential for impact in addition to those more powerful sources that are likely to have a much greater impact. The information in the register should enable member states to perform risk assessments to determine the scale of effect of impulsive sounds in their marine waters. To achieve this, there is a need for more detail in the register in addition to the temporal and spatial information, of which the source level is the most important; this will enable a better assessment of the area impacted by impulsive sounds.

The main items in the register needed to derive the amount of activities are (1) identification and description of the pulse-generating activity, (2) day, (3) location, and (4) source level.

Once a register is established, it will be possible to determine the spatial and temporal distribution of all impulsive noise sources. The actual impact of a single activity may vary depending on context (see Ellison et al. 2012), but the proposed register for impulsive noise would enable the determination of the magnitude of the cumulative impact of sound-generating activities, including assessment on a wider spatial and temporal scale, for instance, regional seas. This quantified risk assessment of impulsive noise sources could be used in the future to determine policy targets. It should also be possible to establish a baseline of “current condition.”

3 Monitoring Guidance for Ambient Noise

3.1 Aim/Effect Addressed by Ambient-Noise Indicator

Shipping activity has increased over the past 50 years, and this very likely has led to increased noise levels, although no suitable measurements are available from EU waters, and at a global scale, evidence of increased noise is limited to the Pacific Ocean (Andrew et al. 2011). It has been suggested that this assumed increase in ambient noise might result in the masking of biologically relevant signals (e.g., communication calls in marine mammals and fishes), considerably reducing the range over which individuals are able to exchange information. It is also known that marine mammals alter their communication signals in noisy environments; although this can be seen as a natural coping mechanism, the need to adapt might still have adverse consequences. It is further assumed that prolonged exposure to increased ambient noise leads to physiological and behavioral stress. Thus chronic exposure to noise may cause permanent impairment to important biological functions and may lead to consequences that are as severe as those induced by acute exposure (Tasker et al. 2010). The frequencies chosen in the Commission Decision are considered to be representative of shipping noise and would serve to characterize trends in ambient noise as formally required by the indicator. However, trend information on its own is not sufficient to assess whether GES has been achieved, which is an overarching aim of the MSFD. Trends indicate whether the actual pressure on the environment (e.g., shipping noise) is rising or falling, but to describe GES, actual levels, based on a wider overview of the area, created by a combination of modeling and mapping will be needed to define the levels required to reach GES.

3.2 Advice on Measuring and Modeling

To capture trends, it is not necessary to describe the complete spatial noise field; a limited number of strategically located monitoring stations (measurement locations) would suffice. However, it is considered that the use of models that combine data from measurements and noise sources with predictions of propagation loss will contribute directly to effective ambient-noise monitoring and assessment against an indicator. Measurements will also be required to ground such models against data from specific locations. There are several reasons to use modeling: (1) to create noise maps that facilitate trend estimation in a more cost-effective manner; (2) to identify trends for different source types by directly identifying the cause of any fluctuations, thus facilitating mitigation action; (3) to permit the removal of selected sources if they do not cause a departure from GES (such as natural sources of sound both biotic and abiotic, e.g., lightning); and (4) to provide member states with a better overview of the actual levels and distribution of levels across their sea area and thereby identify departures from GES. In addition, modeling has a number of advantages that could contribute to a greater understanding of the likely impacts of noise in the future: (5) to possibly predict the effect of future changes (forecast, e.g., what is the expected effect of a certain percentage increase in shipping traffic, assuming no noise mitigation, in the eastern Baltic over the next years) and to reconstruct a history of the past (hindcast) and (6) to make predictions about the efficacy of alternative mitigation actions.

The use of models and sound maps is therefore not seen as an extra requirement to the measuring of ambient noise but rather as a way of obtaining better results at lower costs. However, member states should be careful not to shift the balance too much in favor of modeling only but to ensure that modeling be validated or corrected with measurements. The first TSG Noise report (van der Graaf et al. 2012) described the standards with which the measurement equipment should comply. The second TSG Noise report (Dekeling et al. 2014) provided the initial standards and definitions clarifying what is needed for an appropriate modeling approach.

3.3 Averaging Method for Ambient Noise

The Commission Decision requires member states to determine the average value of the ambient noise. In the first report of TSG Noise, the need for considering different averaging methods was identified and the use of the arithmetic mean was proposed (van der Graaf et al. 2012); however, at that time, TSG Noise did not elaborate on all

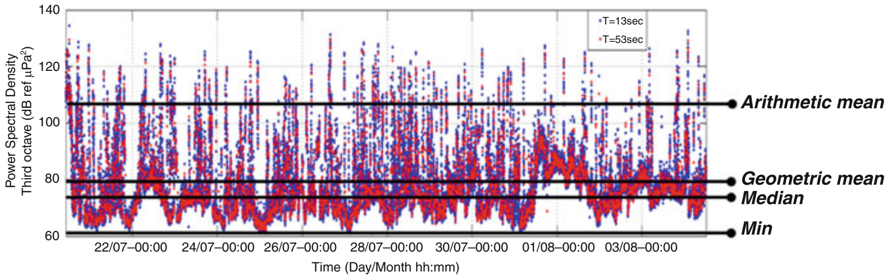


Fig. 24.2 Example of ~14 days of continuous measurement in the 125-Hz third-octave band made off Cork Harbour (Ireland) entrance during the Science, Technology, Research and Innovation for the Environment (STRIVE) Programme of the Irish Government (*source*: Quiet-Oceans)

the pros and cons of the different averaging methods (as noted in Merchant et al. 2012). In the second TSG Report (Dekeling et al. 2014), a justification is provided based on an analysis of the data of the Preparatory Commission for the Comprehensive Nuclear-Test Ban Treaty Organization (CTBTO; van der Schaar et al. 2014).

The different averaging methods were evaluated against the following criteria: (1) the method needs to be robust to minor changes or differences in implementation, (2) the method needs to be physically meaningful and representative of a large enough region to justify its use as an indicator of GES; (3) the method should be practical (simple to implement); and (4) the method should be compatible with comparable regulations or procedures (a desirable property but not essential).

Of the available averaging methods (arithmetic mean, geometic mean, median, and mode), the arithmetic mean (of samples of squared sound pressure) was the method that complied best, and TSG Noise advises that this method be used to establish the average ambient noise levels. For clarification, see Fig. 24.2 that shows the sound pressure level recorded off Cork Harbour over a period of 14 days. The peaks in the measurements correspond to individual ships passing in close proximity to the hydrophone. The arithmetic mean is the highest value of the different averaging methods and is guaranteed to include the contribution from the known anthropogenic events. To establish the statistical significance of the trend, additional statistical information about the distribution of noise levels as a function of time is necessary. Until better advice becomes available, it is recommended that the complete distribution be retained for this purpose in bins of 1 dB.

3.4 Outline of the Monitoring Program

TSG Noise advises member states within a subregion to work together to establish an ambient-noise monitoring system. No precise locations for deploying equipment necessary to monitor relevant frequency bands of ambient noise have yet been defined. However, a set of guidelines is provided for monitoring strategy and guidance for reporting results.

The ambient-noise indicator (like the impulsive-noise indicator) is a pressure indicator that can be used to document trends and levels of ambient noise in an area of interest. For capturing the trend, a limited set of monitoring stations per region/basin should suffice to satisfy the requirements of the indicator. This is dependent on the available information regarding the spatial distribution of activities in each region. In deepwater regions, a single measurement point (at low frequency) may be representative of a wider region because low-frequency sound propagates well in deep water. Low-frequency propagation is more variable (because of higher transmission loss) in shallow water and so more measurements may be required. Even in deep water, there may be factors affecting the measured values; sound channels are likely to exist, resulting in convergence zones.

TSG Noise also provided an initial set of rules for the placement of measurement devices; for more details, see Dekeling et al. (2014).

4 Main Results and Conclusions

TSG Noise in 2013 provided the initial recommendations for the monitoring of underwater noise in European waters. The next step is now for member states to set up a register for impulsive noise and a monitoring program for ambient noise. Information about the actual levels of activities or regular measurements of ambient noise has not been available in Europe. Successful implementation of these monitoring programs will reveal information on sounds in European seas that has not previously been described at this geographical scale. In other regions, similar new efforts have started (most notably, the sound-mapping initiative of the National Oceanic and Atmospheric Administration in the United States), and close cooperation is of importance to ensure that these efforts and the EU approach stay compatible from the beginning.

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Chapter 25
Potential Population Consequences of Active Sonar Disturbance in Atlantic Herring: Estimating the Maximum Risk

Lise Doksæter Sivle, Petter Helgevold Kvadsheim, and Michael Ainslie

Abstract Effects of noise on fish populations may be predicted by the population consequence of acoustic disturbance (PCAD) model. We have predicted the potential risk of population disturbance when the highest sound exposure level (SEL) at which adult herring do not respond to naval sonar (SEL_0) is exceeded. When the population density is low (feeding), the risk is low even at high sonar source levels and long-duration exercises (>24 h). With densely packed populations (overwintering), a sonar exercise might expose the entire population to levels $>SEL_0$ within a 24-h exercise period. However, the disturbance will be short and the response threshold used here is highly conservative. It is therefore unlikely that naval sonar will significantly impact the herring population.

Keywords Noise • Naval sonar • Behavioral effects • Population consequence of acoustic disturbance model

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1 Introduction

A number of studies on how anthropogenic sounds in the marine environment might affect fish have been conducted (e.g., Popper et al. 2003; Popper and Hawkins 2012). These are, however, mostly done with short-duration exposure, making it difficult to predict long-term population effects (Tyack 2008). To enable using small-scale, short-term studies to predict long-term population effects, the National Research Council (NRC) of the United States developed the population consequence of acoustic disturbance (PCAD) model, a conceptual model of how to relate acoustic stimuli to potential population effects (National Research Council 2005).

Some military search sonars use frequencies from 1 to 10 kHz. These high-power sound sources may potentially disturb Atlantic herring, which is an important fisheries resource as well as a prey item for fish, birds, and marine mammals in the Norwegian and Barents Seas (Holst et al. 2004). Several controlled-exposure experiments on Atlantic herring have been conducted (Jørgensen et al. 2005; Doksæter et al. 2009, 2012; Sivle et al. 2012), all using relevant naval sonar signals. These studies are short-duration exposures often designed to find thresholds of behavioral changes, tissue damage, or mortality. Here, their combined results are used as input for the PCAD model to estimate the possible effects of real sonar operations on Atlantic herring at a population level.

2 Materials and Methods

The US NRC has developed a four-step conceptual PCAD model to relate single-acoustic disturbance events to potential population effects (National Research Council 2005). Five variables are of interest: sound disturbance, change in behavior, life functions affected, vital rates, and population effects. The four steps describe the relationships between these variables. The model was originally developed for marine mammals, but the concepts are equally applicable to fish. The four steps of the PCAD model are (1) to identify the noise disturbance and relate it to the animal's behavior, (2) to relate the change in behavior to important life functions, (3) to integrate the effects on the life functions from step 2 on the vital rates over daily and seasonal cycles, and (4) to compare the effects on the vital rates of individual fish to the effect on the population. The results from three studies on herring behavior in response to naval sonar are used here as a primary model input. These include two field experiments in two different parts of the herring's annual cycle, overwintering (Doksæter et al. 2009) and during summer feeding migration (Sivle et al. 2012), as well as experiments on herring in net pens throughout all three annual phases (Doksæter et al. 2012). These studies are summarized in Table 25.1. In addition, a study by Jørgensen et al. (2005) has looked at both behavioral responses to sonar and the effect on growth rate, tissue damage, and mortality in juvenile herring.

Table 25.1 Overview of herring experiments

Annual phase	Area	Sonar signal	Study method	Result	SEL_{cum}	SPL_{max}	Reference
Overwintering	Vestfjorden	1–2-kHz sweep 6–7-kHz sweep	Stationary echosounder	No horizontal or vertical avoidance	184	181	Doksæter et al. (2009)
Summer feeding migration	Norwegian Sea	1–2-kHz sweep 6–7-kHz sweep	High-frequency fishery sonar	No vertical avoidance or change in school dynamics	181	176	Sivle et al. (2012)
Summer feeding Overwintering Spring spawning	Net pen (captivity)	1–2-kHz sweep 1-kHz tone	Stationary echosounder and video	No vertical avoidance	168	168	Doksæter et al. (2012)

SEL_{cum} cumulative sound exposure level in dB re 1 μPa^2·s, SPL_{max} maximum sound pressure level in dB re 1 μPa. Doksæter et al. (2009) and Sivle et al. (2012) were conducted in situ, while Doksæter et al. (2012) was conducted on captive herring in net pens. Doksæter et al. (2009) reported only SPL, and SEL values were calculated based on this. For Sivle et al. (2012), SEL was calculated as the SEL_{cum} over the duration of all pings within an experimental session as in Doksæter et al. (2009). For Doksæter et al. (2012), SEL was accumulated when the rectified sound pressure was within 10% of its peak value within 1 pulse, in contrast to Doksæter et al. (2009) and Sivle et al. (2012) where it was calculated over the duration of all pulses within 1 experimental session

3 Results and Discussion

3.1 Step 1

Doksæter et al. (2009, 2012) and Sivle et al. (2012) found no behavioral response at the tested sound exposure levels (SELs; Table 25.1), but it is not known how the fish may respond if this level is exceeded. The maximum tested SELs are therefore treated as the lowest possible response threshold ($SEL_0 = 184$ dB re 1 $\mu Pa^2 \cdot s$; Table 25.1), with higher levels having the potential to cause a behavioral response (Sivle et al. 2014). Assuming that the behavioral responses to sonar are similar to typical antipredator responses (Lima and Dill 1990), we expect herring to respond by diving and/or horizontal avoidance (Pitcher et al. 1996; Nøttestad and Axelsen 1999).

3.2 Step 2

Avoidance reactions as described in step 1 have high energetic costs, and severe depletion of energy reserves may reduce gonad development and hence reproductive success (Slotte 1999a), A low condition may prevent herring from spawning (Holst et al. 2004) as well as reducing their ability to migrate to the best feeding grounds (Slotte 1999b). The potential behavior change of relevance here is avoidance, with potentially high energetic costs and associated reduced growth and reproductive successes for individual fish.

3.3 Step 3

The studies of Doksæter et al. (2009, 2012) and Sivle et al. (2012) include both day- and nighttime exposures as well as different seasons (Table 25.1), thus covering daily and seasonal variation in terms of exposure levels up to SEL_0. However, real sonar exercises may involve a longer exposure duration. Consequently, adult herring exposed to sonar at levels up to SEL_0 will not show a behavioral response at any part of the day or year, but SEL_0 may be exceeded by longer sonar operations or higher source levels than those tested experimentally.

3.4 Step 4

Vital rates that might be affected by the described behavioral responses for herring include a reduction in recruitment and reproductive output.

Recruitment is affected by a reduction in the number of juveniles entering the adult population. Even though juvenile herring have been shown to react to naval sonars at high source levels (Jørgensen et al. 2005), the high natural mortality rate for juveniles will make this effect negligible because even a worst-case exercise scenario would expose <0.1% of the juvenile population to levels of a behavioral response (Kvadsheim and Sevaldsen 2005).

Herring may skip spawning if the perceived predation risk is too high (Nøttestad et al. 1996). Assuming a reaction to the naval sonar at levels exceeding SEL_0 following an antipredator response, reproductive output will be reduced for the duration of the sonar exercise. However, spawning is spread over 2 months and a large geographical area (Holst et al. 2004); thus the extent and duration of sonar exercises must be unrealistically high to prevent a significant part of the herring population from spawning.

Reproductive output will also be reduced if a large proportion of the population is in too low a condition to spawn due to energy depletion from costly avoidance reactions to the sonar.

To relate this to the population level, an important aspect is the proportion affected, which depends on its distribution. The population of Atlantic herring examined here is distributed differently throughout the year, from a potentially very dense distribution in the traditional overwintering grounds in Vestfjorden over an area covering 300–600 km^2 to the dispersed distribution during feeding in the Norwegian Sea over an area of 300,000–500,000 km^2 (Holst et al. 2004).

Thus, during overwintering, the risk of exposing a large fraction of the population to levels exceeding SEL_0 is much higher than in summer (Sivle et al. 2014). However, here we have assumed that every exposure exceeding SEL_0 will lead to a behavioral response, causing high energetic depletion and following a significant lowered condition, and must therefore be considered a worst-case scenario and a maximization of the involved risk. Additionally, a moving source vessel will only expose individual fish to such high levels for a short time period and is thus not likely to give a significant biological effect (Sivle et al. 2014).

In conclusion, the results presented here show that the highest risk of exposing a large proportion of the population to sound levels that may cause behavioral responses is during the densely populated overwintering phase. This is, however, based on very conservative estimates of reaction thresholds, and individual fish will only be exposed for short time periods. It may therefore seem rather unlikely that naval exercises will have any significant impact on the Atlantic herring population.

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Chapter 26

Fulfilling EU Laws to Ensure Marine Mammal Protection During Marine Renewable Construction Operations in Scotland

Sarah J. Dolman, Mick Green, Sarah Gregerson, and Caroline R. Weir

Abstract Large-scale offshore renewable energy infrastructure construction in Scottish waters is anticipated in coming decades. An approach being pursued, with a view to preventing short-range marine mammal injury, is the introduction of additional noise sources to intentionally disturb and displace animals from renewable sites over the construction period. To date, no full and transparent consideration has been given to the long-term cost benefits of noise reduction compared with noise-inducing mitigation techniques. It has yet to be determined if the introduction of additional noise is consistent with the objectives of the EU Habitats Directive and the Marine Strategy Framework Directive.

Keywords Marine mammals • Pile driving • Noise • Habitats Directive • Marine Strategy Framework Directive

1 Introduction

In an effort to slow the effects of climate impacts, Scotland has moved toward sources of renewable energy generation. The expansion of marine energy developments is rapid. If all proposed sites are granted consent, Scotland is on target to meet

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its energy generation commitments from renewable sources by producing up to 5 GW by 2020 (Marine Scotland [MS] 2012). To facilitate such large-scale offshore development in the coming decades, associated plans to increase and expand the infrastructure at ports and harbors around the Scottish coast are also being put into place. Expectations are for rapid and massive growth of this sector. The primary concern when considering the potential impact of offshore construction on acoustically sensitive marine fauna, particularly cetaceans, has been injury and disturbance resulting from pile driving of foundations into the seabed.

This paper briefly summarizes the current European legislation relevant to marine mammals and marine development in UK waters, identifies some key impact knowledge gaps regarding pile driving, and then recommends a precautionary approach to ensure compliance with the European Union (EU) Habitats Directive (HD; European Communities 1992) and the Marine Strategy Framework Directive (MSFD; European Parliament and the Council of the European Union 2008). A case study concerning the declining east coast population of *Phoca vitulina* (harbor seals) is provided as an example of a population whose conservation status is unfavorable. As a result, the risks and uncertainties associated with development of multiple developments for this species are high.

2 Regulation

2.1 EU MSFD

The MSFD was adopted in July 2008 and aims to achieve or maintain good environmental status (GES) by 2020 at the latest. Annex I of the MSFD lists 11 descriptors of GES, one of which includes the “Introduction of energy, including underwater noise, is at levels that do not adversely affect the marine environment.” Two Indicators have been developed to deal with this descriptor under the Commission Decision of 1 September 2010. Indicator 11.1.1 is titled ”Distribution in time and place of loud, low and mid frequency impulsive sounds” and is relevant to noise generated from pile driving. The Centre for Environment, Fisheries and Aquaculture Science (European Commission 2011) presented two possible targets for MSFD Indicator 11.1.1 in UK seas, representing high and medium levels of ambition. These would be applicable to anthropogenic sound sources measured over the frequency band of 10 Hz–10 kHz that exceed the energy source level of 183 dB re 1 $\mu Pa^2 m^2 \cdot s$ or the zero-to-peak source level of 224 dB re 1 $\mu Pa^2 m^2$. When these source levels are exceeded, “a decrease” or “no annual increase” in the proportion of days and distribution over areas of 10-min latitude by 12-min longitude (Department of Energy and Climate Change [DECC] oil and gas licensing blocks) and their spatial distribution would be required (Hull et al. 2011).

2.2 EU Habitats and Species Directive

Natura 2000 Species

Tursiops truncatus (bottlenose dolphins), *Phocoena phocoena* (harbor porpoises), *Halichoerus grypus* (gray seals), and harbor seals are listed under Annex II of the EU HD as species that require special areas of conservation [SACs; Article 3(1)]. In Scottish waters, there are one, none, eight, and six SACs for each of these species, respectively, currently designated where these species are a primary reason for site selection. Where SACs have been designated, for any plan or project likely to have a significant effect on the site (either individually or in combination with other plans or projects), an appropriate assessment is required to ensure that proposed developments will not have an adverse effect on the integrity of the SAC [Article 6(3)].

European Protected Species

All cetaceans are listed under Annex IV of the EU HD and as a result are offered "strict protection" (Article 12). These species are defined under domestic legislation as European protected species (EPS) and in the context of marine developments in Scotland, this leads to an assessment of potential significant disturbance and injury to a EPS from a proposed development project and the possible requirement to obtain an EPS license depending on the outcome.

Favorable Conservation Status

One of the main goals of the HD is to maintain or restore favorable conservation status (FCS) habitats and species of community interest in Europe. The aim of the Natura 2000 network is to enable the natural habitats (listed in Annex I) and the habitats of the species (listed in Annex II) to achieve or maintain favorable conservation status. FCS is defined in the HD. Article 17 requires members states to report on the implementation of measures undertaken under the HD to achieve FCS for every Annex II and IV species (including all cetaceans) in its waters every 6 year.

3 Some Key Issues

3.1 Summary of Key Impact Knowledge Gaps

Several reviews of the potential impacts of offshore wind farm development on marine mammals are available (for example, Madsen et al. 2006; Dolman and Simmonds 2010; James 2013). To date, field studies have focused on the harbor porpoise, bottlenose dolphin, and harbor and gray seals. All species have been found to be vulnerable to injury at close range within a few hundred meters (for example, Tougaard et al. 2009; Bailey et al. 2010) and to disturbance and displacement at ranges of tens of kilometers (for example, Carstensen et al. 2006; Tougaard et al. 2009; Bailey et al. 2010; Brandt et al. 2012; Skeate et al. 2012). No data exist regarding potential impacts from offshore wind development on baleen whales. However, there is evidence that baleen whales are vulnerable to injury and disturbances from some other sound sources, for example, air gun sound (e.g., Gedamke et al. 2011; Goldbogen et al. 2013).

3.2 Strategic Research

In recognition of the potential for significant impacts to marine mammals and other species at a national level, a number of work streams have been initiated, including by the Offshore Renewables Joint Industry Programme (ORJIP), a UK-wide initiative that is led by The Crown Estate (TCE), the DECC, and MS. Three of four projects being pursued by ORJIP are focused on understanding strategic issues surrounding the noise impacts on marine mammals. The marine mammal projects are (1) evidence gathering for the population consequences of acoustic disturbance (PCAD) model, (2) underwater noise mitigation technologies for piled foundations in deeper waters, and (3) use of acoustic deterrent devices (ADDs) and improvements to standard mitigation measures during pile driving. A further project is on seabirds (seabird collision risk and avoidance rate monitoring). Each project is progressing at different rates, and currently those that investigate “short-term” fixes (such as ADDs) rather than long-term solutions (noise-reduction techniques) are progressing the fastest.

The wide-scale use of ADDs as a mitigation measure to reduce injury to marine mammals resulting from pile-driving activities will purposefully disturb all marine mammals that come within a defined range of the device. The use of ADDs themselves may cause injury at close range if source levels are high enough. The effectiveness of ADDs to deter the wide range of species that the devices would need to deter is yet to be proven.

For large developments where the installation period may be extended, alternative technologies or engineering solutions (such as the use of bubble curtains, gravity-based systems, or floating platforms) that could reduce noise disturbance may need to be considered (Macleod et al. 2010). Other than not pile driving, actively reducing the source level of the pile-driving apparatus is the most effective method of decreasing the resulting sound levels. Reducing the sound level radiated from the source will reduce both the potential radius over which mortality and injury may occur and the behavioral impacts. It would also reduce the key consenting risks identified, including reducing uncertainties in the assessment of environmental impacts and assessment of cumulative impacts (RenewableUK 2011). As a result, providing consent would be more achievable where licenses to disturb fewer EPS would be required. In addition, reductions in overall noise generated from pile-driving construction works would reduce the pressure on GES targets. Significantly, the progression of

ADDs rather than the development of noise-reducing techniques may conflict with the requirements of the MSFD to reduce noise levels in European waters. Current license applications will be assessed before the ORJIP work stream is complete. In the meantime, planning and marine licensing decisions and advice in the United Kingdom will continue to be made on the "best available" evidence (DECC 2013).

3.3 Cumulative Impacts

A strategic environmental assessment (SEA) at the national level was undertaken for marine renewable energy, and the Scottish Marine Plan that resulted was adopted in 2011 during the Round 3 (R3) and Scottish territorial waters (STW) program of offshore wind development. Although R3 and STW make up the current licensing round, delays in previous Rounds 1 and 2 (R1 and R2, respectively) have meant that construction of some R1 and R2 sites may overlap with those of R3 and STW. Cumulative impacts may result and are likely to be an important consideration once GES indicators are set, particularly if limits are set and sectors are in "competition" for noise generation.

4 Case Study: Harbor Seals and Pile Driving in Scotland

The United Kingdom has assessed the conservation status of the harbor seal in both the 2000–2006 (Joint Nature Conservation Committee 2007) and the draft 2007–2013 reporting rounds as "unfavorable-inadequate." Major declines have now been documented in harbor seal populations around Scotland (Scientific Committee on Seals 2011). As an example, the local east coast population of 241 harbor seals (Scientific Committee on Seals 2011) has been protected under the Firth of Tay and Eden Estuary SAC since 2005 (Scottish Natural Heritage 2006). This population has declined by 84% (Scientific Committee on Seals 2011). Accordingly, the harbor seal Firth of Tay and Eden Estuary SAC objectives are not currently being met. Despite this and as part of The Crown Estate's R3 and STW program, three large offshore wind farms are currently being proposed in the Firth of Forth region. Cumulative impacts will be a considerable issue. A recent study confirms that there is potential for harbor seals to be negatively impacted by marine renewable energy developments, particularly pile driving (Skeate et al. 2012). It is therefore difficult to see how a new development that may further impact the already vulnerable seal population in an SAC designated for their conservation could be granted consent. Applying Article 6(3) of the HD, an appropriate assessment must be carried out and result in a finding of no adverse effect on site integrity. A competent authority must have made certain that a plan or project will not adversely affect the integrity of the site. That is the case where no reasonable scientific doubt remains as to the absence of such effects (Case C-127/02 2004). In considering whether the integrity of a site will be affected, the competent authority must have regard to the conservation objectives of the site. A competent authority may, despite a negative assessment of the implications for the site and in the absence of alternative solutions, permit a plan or project to be carried out for reasons of overriding public interest. However, compensatory measures must be undertaken to ensure that the overall coherence of Natura 2000 is protected. The harbor seal is listed as a priority species and, therefore, such public interest is restricted to human health or public safety.

5 Conclusions

The existing shortcomings and gaps in the current knowledge of pile-driving impacts on marine mammals are extensive. Furthermore, the current guidelines for mitigating impacts on marine mammals only deal with localized death and injury in the immediate vicinity of the sound source. Mitigation measures to protect mammals from death and injury that rely on the animals maintaining a distance from the source and that do not include shutdowns of an active sound source when animals approach within a dangerous sound-level radius are not precautionary. In many areas that contain vulnerable and highly protected species, these may not meet the requirements of European legislation. The wider issues regarding disturbance continue to be very difficult to assess when so little information is available on the sound levels causing these impacts. As a result, other than avoiding sensitive animals altogether in time and space (i.e., through spatiotemporal closures), efforts to reduce noise levels at the source are the most effective way to reduce impacts. Adoption of strong targets for GES that require member states to take action to reduce noise would go a considerable distance to overcome issues relating to injury and disturbance. They would also provide clarity to developers and regulators.

There remains a high level of uncertainty surrounding the impacts of pile driving and there are high risks for some species. Considering the scale of pile driving that is anticipated during R3 and in STW, a precautionary approach to management is required. This is particularly true in areas where marine species are declining and where Natura 2000 conservation objectives are already not being met, as is the case for the harbor seal Forth and Tay Estuary SAC.

Competent and relevant authorities must exercise their functions so as to secure compliance with the HD and be in line with the MSFD. MS must make decisions surrounding the licensing of east coast developments (including other regional developments), while maintaining the conservation objectives of the harbor seal SAC over the long term, when this priority species is undergoing a “substantial [population] decline” (Sparling et al. 2011). European case law confirms that the precautionary principle is required for any assessment of effects on site integrity and precautionary assumptions within the early licensing conditions have been recommended to ensure legal compliance (Macleod et al. 2010).

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Chapter 27

Expert Elicitation Methods in Quantifying the Consequences of Acoustic Disturbance from Offshore Renewable Energy Developments

Carl Donovan, John Harwood, Stephanie King, Cormac Booth, Bruno Caneco, and Cameron Walker

Abstract There are many developments for offshore renewable energy around the United Kingdom whose installation typically produces large amounts of far-reaching noise, potentially disturbing many marine mammals. The potential to affect the favorable conservation status of many species means extensive environmental impact assessment requirements for the licensing of such installation activities. Quantification of such complex risk problems is difficult and much of the key information is not readily available. Expert elicitation methods can be employed in such pressing cases. We describe the methodology used in an expert elicitation study conducted in the United Kingdom for combining expert opinions based on statistical distributions and copula-like methods.

Keywords Expert elicitation • Renewable energy • Noise

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1 Introduction

The United Kingdom has ambitious targets for the proportion of its energy requirements to be met from renewable sources in the near future. A large component of this will be met by offshore wind farms currently in operation or under construction, and further large expansions are planned. Installation of such turbines produces large amounts of underwater noise due to periods of pile driving, noise that is far-reaching and has the potential to disturb populations of marine mammals for extended periods. There is justifiable concern about the potential impacts of anthropogenic acoustic disturbance on marine mammals, with Southall et al. (2007) serving as a notable recent review.

These concerns led to the formation of a panel by the Council of the United States National Academy of Sciences (National Research Council 2005), which, in turn, led to a model framework termed population consequences of acoustic disturbance (PCAD) and later the more general population consequences of disturbance (PCoD). These are detailed in Chapter 49 by Harwood et al.

Subsequently, there have been attempts to create models for some species and situations using the PCoD framework (a form of interim PCoD). Chapter 49 by Harwood et al. presents the background to this, which seeks to model the population impacts of offshore renewable energy development on several marine mammal species.

Quantification of such complex risk problems is inherently difficult and much of the key information is not readily available. This paper is concerned with combining the opinions on relevant parameters elicited from experts in the field.

2 The Data

Expert elicitation is a technique that has been widely used in conservation science when there is a relative lack of data but an urgent need for conservation decisions (Martin et al. 2012). For PCoD models in the context of offshore renewable energy development, we consider acoustic behavioral disturbances that may affect the survival probability of an individual female's offspring. The actual mechanisms underpinning this effect might be various (separation of calf and mother, decreased energy intake, or increased energy expenditure), but basic survival probability information is needed for a simple PCoD implementation. Empirical information of this type is not available for most marine mammal species, so it is sought here through expert opinions.

As described in Chapter 49 by Harwood et al., information was solicited from experts in the field via repeated online surveys and meetings. The four-step interval approach of Speirs-Bridge et al. (2010) was used to provide estimates of the confidence that experts attached to their opinions. The main data we consider here relate

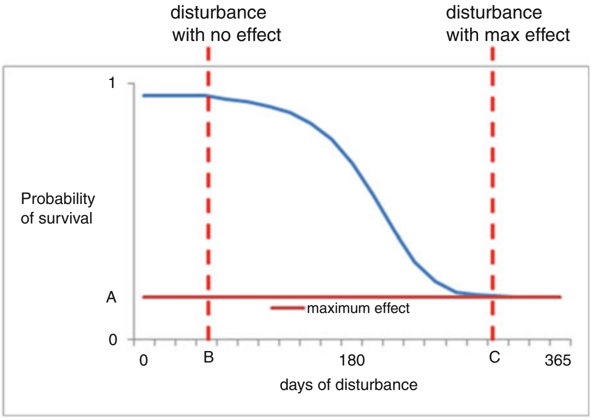

Fig. 27.1 Hypothetical curve that requires parameterization from expert opinions. Three parameters are required: the point at which the curve falls from probability = 1 (*parameter/line B*), the lower bound (*parameter/line A*), and the point at which the curve meets line A (*parameter/line C*)

to the potential population consequences of hearing damage on the vital rates of adult/calf/juvenile survival and the probability of giving birth in the context of offshore renewable energy developments.

The experts were queried for estimates on the effects of permanent hearing threshold shift (PTS) and disturbance on these vital rates. The estimate reflected his or her best guesses at two sets of parameters: (1) the potential effect of hearing damage (PTS in a specified frequency range) on survival and, for mature females, on the probability of giving birth, and (2) three parameters that determined the relationship between the number of days of disturbance an individual might experience in a year and its survival and, for mature females, the probability of giving birth. Figure 27.1 shows how these parameters determine the shape of the relationship between disturbance and survival or fertility. Parameter A defines the maximum effect of disturbance on survival, parameter B defines the amount of disturbance an individual can tolerate before it has any effect on survival or fertility, and parameter C defines how many days of disturbance are required to have the maximum effect on survival or fertility.

The experts were also prompted to provide information on the confidence/uncertainty associated with their guesses. The uncertainty in the expert's estimates were provided by (1) a range that "bounds" the estimate and (2) a level of confidence about their guess.

3 Combining Expert Opinions

Statistical models that were consistent with each expert's best guess and associated upper and lower bounds were generated using some of the approaches described by Genest and Zidek (1986), Garthwaite et al. (2005), and Albert et al. (2012). Two main cases arise here: probability density functions (PDFs) for single parameters (e.g., the effect of PTS at 1–2 kHz on the probability of survival) and multivariate PDFs that characterize curves as seen in Fig. 27.1. Ultimately, these are to be used in a Monte Carlo fashion to provide inputs to the PCoD protocol, i.e., random draws will be required from these.

For multivariate treatments, simulation methods were used (Iman and Conover 1982). These allow a multivariate distribution of correlated variables to be defined using arbitrary marginal distributions and a separate correlation structure. The general process in these two cases is described in Sections 3.1 and 3.2.

3.1 Single Parameters

The single parameter case is straightforward and well studied (e.g., Genest and Zidek 1986). An example in our study would be the effect of PTS, at 1–2 kHz, on the probability of survival. This involves a single parameter in a 0–1 bounded domain. For single parameters, (1) the experts' estimates were used to fit appropriate PDFs such as the gamma, beta, truncated normal, uniform, or triangular distributions. For example, their best guess and bounds could define a triangular PDF or lead to a particular beta distribution. In this way, each expert's opinion was encapsulated in an individualized probability distribution, and (2) the individual distributions were effectively combined as a weighted sum, subsequently normalized, to give a collected PDF for the parameter.

3.2 Multiple Correlated Parameters

The multiparameter problems are of particular interest because of their relative complexity. Some complication occurs at the solicitation stage because it is particularly difficult to solicit the opinion of experts on parameters that are not independent of one another, i.e., are correlated in some way. For example, a 3-parameter problem like Fig. 27.1 may have an additional three correlation parameters reflecting the interparameter relationships that are difficult to solicit directly from the experts (but may be estimated from their responses with regard to the other parameters).

In all cases, the expert's opinions are used to define PDFs for the PCoD parameters, which will be sampled for Monte Carlo simulations. In short, we require methods that allow simulation from multivariate PDFs with arbitrary marginal distributions and general correlation structure.

Taking a broad view of the statistical literature, there are various potential methods applicable to the current problem. Copulas are an obvious choice, attributed to Sklar (1959) and subsequently studied extensively by Genest and MacKay (1986), Schweizer (1991), and Jouini and Clemen (1996). Relatedly, there is the rank-order correlation method of Iman and Conover (1982). Both methods have a previous track record, particularly in applications of financial risk management, and fulfil our requirements for arbitrarily defined marginal distributions and intervariable correlations. The Iman–Conover method is favored here for computational reasons, although copulas could also serve, details of which can be found in Joe (1997) among others.

The Iman–Conover method induces a desired rank correlation matrix on a multivariate input random variable for use in simulation. This method is simple to use and preserves the exact form of the marginal distributions on the input variables. In essence, draws can be taken independently from marginal distributions and used to form a multivariate distribution with the desired correlation structure. The draws from the marginal distribution are structured so that their rank correlation is close to those correlated draws from a reference distribution. Technical details of the method can be found in Iman and Conover (1982). The method was coded from first principles in R for the purposes of this study (R Core Development Team 2013).

In the multivariable case, the parameters are a mix of 0–1 bounded and nonnegative domains and the following processes were applied. (1) The marginal distributions for the three parameters were estimated by creating distributions for each expert based on their best estimates and their bounds for those estimates, e.g., used to define gamma, beta, triangular, and truncated normal distributions as appropriate. (2) Correlation matrices were estimated from the collective expert's point estimates. (3) Random draws were taken via the Iman–Conover method from each expert's multivariate distribution, which is a mix of estimated marginal distributions and governing correlation structure. (4) Collectively, the experts' multivariate distributions were sampled intensively, in proportion with their confidence in their opinions.

An example of this process for bottlenose dolphins is shown in Fig. 27.2, which summarizes 10,000 draws from the collected expert's multivariate PDF for the three parameters governing the curve in Fig. 27.1. The experts' assessments of their confidence in their estimates are easily incorporated under this framework because the probability of drawing from a particular expert's distribution can be made proportional to their confidence.

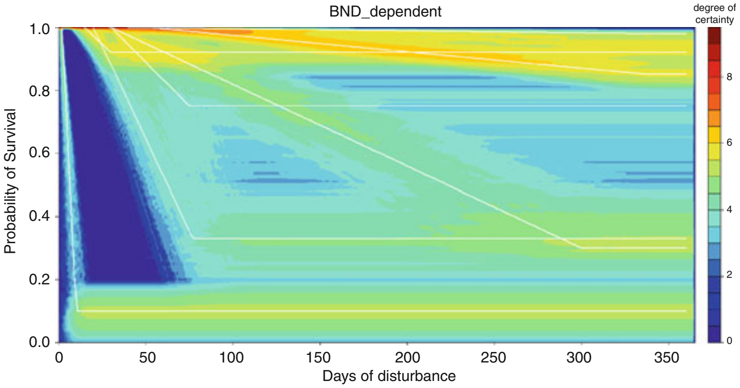

Fig. 27.2 Mass of curves generated under resampling using the expert opinions of parameter values, their estimates of uncertainty, and confidence in their estimates. The *color scale* represents the (log $x+1$) number of times the randomly drawn curves agreed at a particular point (at a certain resolution) and serves as an index of the most likely probability values for a given time

4 Discussion

It is immediately apparent in our example that there are distinct, differing opinions among the experts. In particular, there is a group that clearly believe that the impacts are relatively sudden and extreme, whereas another group believes the impacts to be gradual and minor. There are some indications of opinions between these extremes, but they are less pronounced. This uncertainty in opinion is naturally propagated via Monte Carlo through any of the following simulation/modeling, i.e., if these estimates are indeed critical to PCoD outcomes, then the resulting predictions of consequences will be correspondingly uncertain. In this case, the differences may represent inherently different views on the system under study or may represent different ways in which the question as posed has been understood. For example, some experts may imagine a situation where animals are free to flee disturbances, whereas others may imagine a situation where movement is constrained through site fidelity. Other solicitation methods can be approached to refine the estimates, such as the Delphi method (MacMillan and Marshall 2006).

Expert elicitation is naturally no substitute for properly conducted studies into particular problems. However, it does serve as a coherent approach for opinion-based estimates when there is an urgent need for conservation decisions that precedes the requisite science. Consulting a range of experts and appropriately querying bounds on their estimates and confidence provides a probabilistic view of expert opinion. Combined with a Monte Carlo approach, uncertainty is naturally propagated through to advice based on these opinions, e.g., through model predictions. Correlated multiparameter problems are difficult to tackle, particularly in terms of soliciting an expert opinion on correlations, but there are existing statistical methods that can be employed, specifically, methods such as Iman–Conover that allow easy specification of general correlated multivariate PDFs and the subsequent simulation from these.

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Chapter 28
Masking Experiments in Humans and Birds Using Anthropogenic Noises

Robert J. Dooling and Sandra H. Blumenrath

Abstract This study investigated the masking of pure tones by anthropogenic noises in humans and birds. Bird experiments were conducted in the laboratory using operant conditioning and psychophysical procedures but with anthropogenic noises rather than white noise. Humans were tested using equivalent psychophysical procedures in the field with ambient background noise. Results show that for both humans and birds published critical ratios can be used to predict the masking thresholds for pure tones by these complex noises. Thus, the species' critical ratio can be used to estimate the effect of anthropogenic environmental noises on the perception of communication and other biologically relevant sounds.

Keywords Detection • Noise • Hearing

1 Introduction

The masking of vocal signals and other sounds may prove to be the most insidious effect of noise on wildlife because it can potentially disrupt normal behavior patterns and adversely impact survival (Slabbekoorn and Ripmeester 2007). Most commonly, masking refers to the increase in thresholds for the detection or discrimination of different sounds caused by the presence of another sound. We therefore believe that an important step in understanding how noise limits animal communication or interferes with the detection of other biologically important sounds in natural environments is to consider communication from the receiver's perspective and to include species differences in auditory sensitivity. At the receiver's end, temporarily or permanently increased noise levels can mask sounds that would give away a lurking predator or the associated alarm calls from other animals. In addition, acoustic signals in birds, for instance, are important for territory defense and mate attraction (Catchpole and Slater 1995), diminishing the birds' reproductive success and survival when vocal communication efficiency is reduced by marked increases in noise.

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Therefore, understanding how and to what extent masking like this occurs and whether there are species differences is fundamental in determining the impact level of a noise source (Okanoya and Dooling 1987; Dooling et al. 2000).

1.1 Previous Studies

From laboratory studies of humans and birds, there is a long and rich literature describing the masking of pure tones by wideband noise, and this critical ratio function has been described for humans and a variety of other mammals, birds, and aquatic animals (Fay 1988; Dooling et al. 2000). For humans and birds, at least, there are also data on the masking of vocal signals by noise (see, e.g., Lohr et al. 2003). Using both pure-tone data and data for the masking of vocal signals, we presented in an earlier paper a model for defining a bird's active auditory space in a noisy environment based solely on the critical ratio, the masking of a pure tone by broadband noise (Dooling and Blumenrath 2013). The model is based on experimental studies with spectrally and temporally uniform white noise and clearly shows significant reductions in effective communication distances when noise masks vocal signals (Fig. 28.1). Moreover,

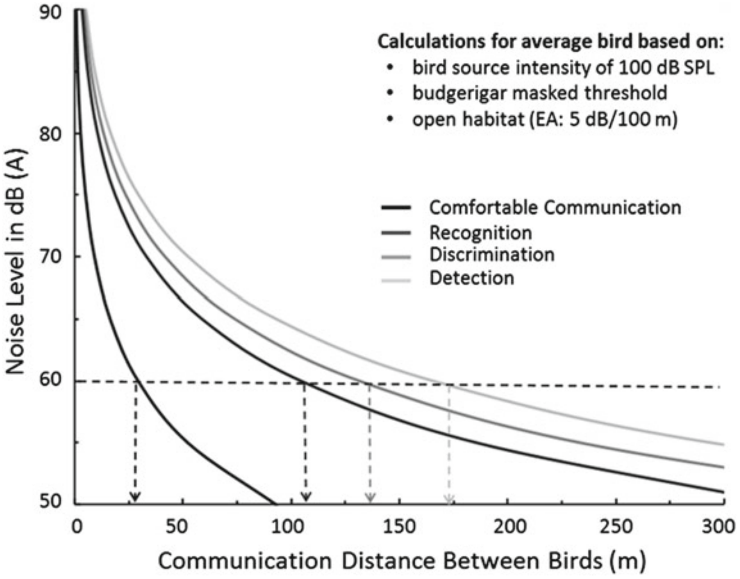

Fig. 28.1 Schematic of a model for predicting the effects of masking noises on animal communication. The model shows the relationships among noise level, distance of the bird from the noise source, and the different effects of the noise on birds. It is based on experimental studies (Lohr et al. 2003) with spectrally and temporally uniform white noise with different signal-to-noise ratios (SNRs) affecting detection, discrimination, and recognition of vocal signals. The SNR needed for comfortable communication is taken from human reports during speech communication. *SPL* sound pressure level. From Dooling and Blumenrath (2013)

from psychophysical experiments with birds in the laboratory, we know that the signal-to-noise ratio (SNR) required for recognition of vocalizations is 2–3 dB higher than that required for discrimination and that the SNR required for discrimination is 2–3 dB higher than that required for detection (Lohr et al. 2003) when broadband noise is used as a masker. With this information gained from psychophysical experiments in conjunction with information on noise levels at the source and how sounds attenuate as they travel through the environment, we can estimate the effect on communication at different distances from the noise source. In a noisy environment, birds must be in close proximity to communicate comfortably, although they could still detect each other's vocalizations against a background noise at a much greater distance (Dooling and Blumenrath 2013).

1.2 Untested Assumptions in the Existing Model

Naturally occurring abiotic noises are typically characterized by variable source-specific spectral and temporal patterns, and one could expect these noises to differ in their overall masking effects compared with traditionally used white noise maskers. Although this model provides a simple conceptual and computational way to approach the effects of anthropogenic noise on vocal communication in birds, there are a number of untested assumptions that go into the model. First, we assume that critical ratios measured in the laboratory for both humans and birds are at least approximately realized in more natural situations. Second, we assume that the general power spectrum model of masking holds in that noise in the spectral region of the signal is most effective in masking that signal even for anthropogenic noises that do not have a flat spectrum. In this paper, we tested these two assumptions.

2 Human Masked Thresholds Measured in the Field

Experiments with four normal-hearing human participants were conducted in a small recreational park in a suburban neighborhood in the vicinity of the University of Maryland, College Park. Sound files were stored on a laptop computer and played through a Samson speaker with an integrated amplifier. The human subject stood 50 m away from the loudspeaker. A software program was customized to replicate the psychoacoustic tasks performed by birds in the laboratory by controlling and randomizing the sound level and order of playback within specified settings and by recording the participant's responses (hit, miss, false alarm, correct rejection). As test stimuli, we used pure tones at 0.5, 1, 2, and 4 kHz and randomly decreased their levels in 5-dB steps. A recording setup at the position of the human listener recorded the signal plus noise for each experimental trial. The recording equipment consisted of a Larson Davis microphone and a Sound Device recorder. The participant was instructed to raise his/her hand when he/she detected a sound, and the experimenter recorded this response in the program.

Under natural conditions, both the level of the noise and the level of the tone varied considerably from moment to moment. However, regardless of the absolute level of either the signal or the spectrum level of the noise around 1 kHz, the SNR resulting in a 50% correct detection level corresponded well with published critical ratios for human listeners.

3 Bird Masked Thresholds Measured in the Laboratory Using Anthropogenic Noises

The experiments with four canaries and three budgerigars were conducted in a psychophysical setup consisting of an operant conditioning chamber with a wire cage, food hopper, and two LED response keys. Experimental tasks were controlled by a computer program interfacing with a Tucker-Davis Technologies (TDT) system III (see, e.g., Lohr et al. 2003). We used representative noise recordings from a drilling rig, helicopter, motorcycle, snowmobile, and a small aircraft that were all recorded in a quiet natural area in or close to a Colorado national park. In addition, we recorded noise from a suburban neighborhood consisting of constant levels of both traffic and wildlife noise. The test stimuli were pure tones at 1, 2, and 4 kHz played at a maximum level of 60 dB sound pressure level (SPL; A, fast setting) and decreased in 5-dB steps. The noise was played back continuously as a 2-min background loop. We performed all sound level measurements and stimulus calibrations in the setup at a distance of 0.5 m from the speaker where the receiving bird is typically located.

An example spectrum of a snowmobile noise is shown in Fig. 28.2a. The SNR at the masked threshold was calculated from the tone level at threshold and the noise spectrum level in the 1/3-octave band surrounding the pure tone. These critical ratios

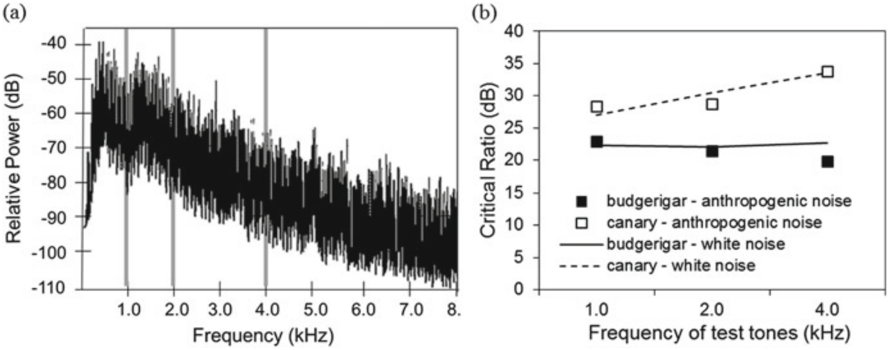

Fig. 28.2 Frequency spectrum of a representative anthropogenic noise segment from a snowmobile recording (**a**) and avian critical ratios obtained for this noise masker (**b**). Comparisons are made to critical ratios based on spectrally uniform white noise. *Vertical lines* in the noise spectrum refer to the frequencies of the test tones. The noise was band-pass filtered with low- and high-frequency cutoffs at 0.5 and 8.0 kHz, respectively

for canaries and budgerigars using snowmobile noise are shown in Fig. 28.2b in relation to the published critical ratio data for these species using white noise (Okanoya and Dooling 1987). Canaries have much larger critical ratios than budgerigars when both broadband white noise and anthropogenic noise are used as maskers. For both canaries and budgerigars, the masking effects of the two kinds of maskers are similar.

4 Discussion

Our results suggest that noise masking in the natural world, specifically masking from anthropogenic noises such as the ones tested here, are approximated by masking studies in the laboratory using spectrally uniform white noise. In practical terms, this means that with knowledge of the species critical ratio in hand as well as the acoustic characteristics of both biologically relevant sounds and anthropogenic noise at the location of the listening animal, one can arrive at an estimate of the sound's effective distance or active space and the way in which anthropogenic noise will affect acoustic communication. Temporal variation in natural and anthropogenic noises, however, can be expected to have an effect on the instant-by-instant audibility of sounds (Bee et al. 2007; Vélez et al. 2007).

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Chapter 29
Documenting and Assessing Dolphin Calls and Ambient and Anthropogenic Noise Levels via PAM and a SPL Meter

Kathleen M. Dudzinski, Kelly Melillo-Sweeting, and Justin D. Gregg

Abstract Song Meter SM2M marine recorders were deployed to document dolphin calls and ambient and anthropogenic noise. Recordings from Bimini were split into 2-h segments; no segment was without dolphin calls. At Dolphin Encounters, average noise levels ranged from 110 to 125 dB; the highest source level was 147.98 dB re 1 μPa at 1 m. Average ambient-noise levels documented at 4 sites in Guam were below 118 dB re 1 μPa at 1 m. These data were compared with values from a custom-built sound pressure level (SPL) meter and confirm that the SM2M recorder is a useful tool for assessing animal calls and ambient and anthropogenic noise levels.

Keywords Autonomous passive acoustic monitoring • Ambient-noise levels • Vocalizations • Marine mammal monitoring

1 Introduction

Passive acoustic monitoring (PAM) is a cost-effective tool for documenting acoustic activity from naturally occurring, biological sound sources spanning weeks, months, or years with the least amount of direct labor, highest degree of safety to human observers, and least disruption to study species (Mellinger et al. 2007). PAM has been used to document the vocal behavior of species in a given study area (Clark et al. 2010); to assess species distribution (Kimura et al. 2010), habitat use (Munger et al. 2008), or migratory behavior (Simon et al. 2010); and to document interactions between individuals and groups in an identified geographic area.

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Anthropogenic noise can be monitored via methods similar to those used to document calls but can also be monitored via a sound pressure level (SPL) meter to assess both received and source noise levels for monitoring or mitigation (Mellinger et al. 2007). A particular advantage of PAM over methods involving human operators is the possibility to obtain long data series from remote areas or during periods when weather or other conditions make it unsafe or impossible for an observer to operate.

This paper focuses on a comparison of the application of a PAM unit deployed in three different study sites for purposes of documenting ambient and anthropogenic noise levels as well as dolphin calls. Additionally, SPL values collected via PAM were compared with recordings obtained with a custom SPL meter.

2 Methods

2.1 Equipment

The Song Meter SM2M Marine Recorder

The Song Meter SM2M marine recorder is a submersible 16-bit digital recorder designed for short- or long-term deployments in fresh- or salt-water to depths of up to 150 m (www.wildlifeacoustics.com). The housing is 165 mm in diameter and 794 mm in length. With a full battery, the recorder weighs 13.5 kg in air, with 1.5 kg of buoyancy. Although the recorder has multiple power options (up to 32 LSD NiMH, alkaline, or lithium manganese D-cell batteries), we used between 8 and 32 alkaline batteries depending on deployment length. Sample rates are specific to the deployment site. Each SM2M recorder had an integrated hydrophone (sensitivity of -165 ± 1 dB re 1 V/μPa, with a recording bandwidth of 2–48 kHz and a flat frequency response).

SPL Meter

The ST1400ENV SPL meter, partnered with a CR1 omnidirectional hydrophone (sensitivity −197.98 dB, capacitance 9.8 nF, dissipation 0.017%; Serial No. CR1-9,041-15, Sensor Technology Ltd.), is a calibrated mobile data recorder and sound level monitor with National Institute of Standards and Technology (NIST)-certified calibration. The ST1400ENV SPL meter is portable, self-contained, and designed to record underwater sounds while simultaneously monitoring and logging SPLs.

2.2 Data Collection

SM2M recorders were used to collect dolphin calls off Bimini, The Bahamas, to assess both ambient and anthropogenic received noise levels at Dolphin Encounters (DE) in Nassau, The Bahamas, and to access baseline ambient-noise levels in

Table 29.1 SM2M settings per deployment and location

	Gain (dB)	Filter (Hz)	Sample rate (kHz)	Record cycle	Deployment duration
Bimini 1	12	3	44.1	Continuous	12 days
Bimini 2	12	1	44.1	Continuous	13 days
DE	0	2	44.1	Continuous	12 h
SC	0	2	32	Continuous	72 h

DE Dolphin Encounters, *SC* Sumay Cove, Naval Base Guam

Sumay Cove, Naval Base Guam (SC). Our settings varied slightly by deployment and location (Table 29.1), but all data were recorded to SDHC flash memory cards. The ST1400ENV SPL meter was used to document ambient and anthropogenic received noise at DE.

Study Sites

Bimini

The waters north and west of North Bimini are the site of long-term research into wild dolphin behavior, ongoing since 2001 (Melillo et al. 2009; Greene et al. 2011; Melillo-Sweeting and Turnbull 2011; Dudzinski et al. 2012). The area where dolphins are most regularly observed generally consists of a white, sandy seafloor devoid of a major reef habitat. A small population (~120 individuals) of *Stenella frontalis* (Atlantic spotted dolphins) are thought to be year-round residents near Bimini (Melillo et al. 2009), with *Tursiops truncatus* (bottlenose dolphins) also present. The *Stenella* study group is considered habituated to boats and human swimmers.

DE

DE is a natural seawater facility located within the lagoon of Blue Lagoon Island, near Nassau, The Bahamas. The dolphin habitat is over 3 acres in surface area, with depths ranging from shore to 7.62 m depending on the pool. There were 20 *Tursiops truncatus* resident in the DE facility during this study. Participants in dolphin swim/encounter programs arrive at the island via one of three DE passenger ferries that dock at the western edge of the dolphin habitat.

SC

Sumay Peninsula is located between SC (to the southeast) and Clipper Cove (to the northwest) on the southern edge of Outer Apra Harbor, Guam. Underwater ambient-noise levels were recorded with two SM2M units inside SC near the boat ramp and marina, in the SC Channel, in the Clipper Cove Channel, and in Outer Apra Harbor for a minimum of 3 full 24-h cycles (i.e., 72 h/site) to determine baseline ambient-sound levels.

Deployment Procedures

Bimini

The SM2M unit was deployed twice: from 29 July to 9 August 2011 (25°51.098′N, 79°15.914′W, to 10.06 m) and from 18 to 30 September 2011 (25°52.563′N, 79°14.014′W, to 9.86 m), with a cement-filled 5-gal bucket serving as anchor (Fig. 29.1).

DE

Data were collected from 5 to 7 November 2011 during 3-day and 2-night deployments, each ~12 h long, in five different locations in the dolphin habitat to depths ranging from ~3 to 4 m. Vessel arrival times and duration of the stay at the dock were documented during day deployments. Vessel arrival and departure times at the start and end of night recording sessions were only noted.

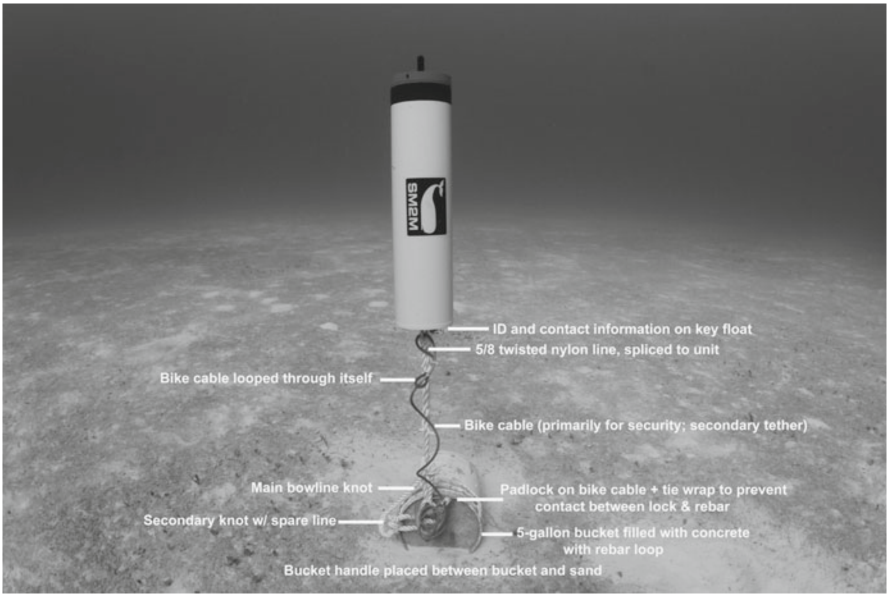

Fig. 29.1 SM2M unit deployed near Bimini, The Bahamas. Photo courtesy of Al Sweeting, Jr

SC

Deployment of two SM2M recorders was similar to procedures for the Bimini deployments. Each recorder was tethered to a 5-gal cement-filled weight (anchor) and lowered over the vessel side via a guideline. Because deployments were in an area with active vessel traffic, surface float buoys were used during each deployment.

Data Analyses

Bimini: Dolphin Vocal Data

Audio files were examined for the presence of dolphin calls (e.g., whistles, clicks, brays) via manual review of spectrograms; continuous audio data were parsed into 30-min files. Only call presence was of interest; if a call was detected in a file, whether at the start, middle or end, the file was identified as possessing calls. After confirmation of call(s), the next file was reviewed, and so on for each 30-min file.

DE: Noise Levels

Audio data were extracted and analyzed to assess noise levels. Average ambient levels were examined for diurnal patterns. Each 30-min audio file was time stamped and compared with surface notes regarding weather and anthropogenic activity (e.g., boat arrival). Received levels at the SM2M unit were identified as related to boat present versus boat absent. Source levels at the vessel were estimated using a modified equation as a compromise between cylindrical and spherical spreading: $\mathrm{SL} = \mathrm{RL} + 15\log R$, where SL is source level, RL is received level, and R is the range in meters between SL and RL. (Note: the distance between the SM2M unit and the vessel engine was measured directly.)

SC: Baseline Recordings

The log scale waveform view in Song Scope was used to obtain average decibel values per 15 min of recording per SM2M dataset. The calibrated gain and hydrophone sensitivity values provided with the SM2M unit were used in these calculations. The resultant ambient received decibel sound level has an error of ±1 dB carried over from the hydrophone specification.

3 Results

3.1 Dolphin Calls Near Bimini

One SM2M unit was deployed twice near Bimini, each for an ~2-weeks period. For deployment 1, the day was divided into 2-h blocks and no 2-h period was without dolphin calls. A range of 8–11 days with call detections was found for each of the 12 segments across the 12 days ($n=12$, mean = 9.8, SD = 1.11). The 2 blocks spanning 1,001–1,400 h yielded the lowest number of days with detections at 8 detections/block. Data from the second deployment are being analyzed to determine if the summer vocal pattern persists into the autumn in the study area.

3.2 Noise Levels at DE

The average noise levels collected with the SM2M recorder ranged from ~110 to 125 dB re 1 μPa at 1 m when associated with vessel noise. The average noise levels recorded with the SPL meter ranged from 105.87 to 107.56 re 1 μPa at 1 m when associated with vessel noise. Each pool at DE's Blue Lagoon Island facility is exposed to varying levels of noise from different sources (e.g., vessel engines, wave action). The SM2M recorder was deployed during day and night periods, with little difference documented between day and night for RL values (Table 29.2). SL values were calculated for only day deployments because vessel presence was not documented during night deployments.

Table 29.2 Received and calculated source noise levels for each SM2M deployment

Deployment	Received level (dB)	Source level (dB)
Location 1, Day	117.12 (116.39)	134.34 (134.53)
Range	108.4–130.32	119.2–147.9
Location 2, Night	114.15 (113.46)	Not calculated
Range	107.83–124.56	
Location 3, Day	124.36 (123.96)	Not available
Range	119.44–131.47	
Location 4, Night	115.10 (115.05)	Not calculated
Range	111.45–120.18	
Location 5, Day	115.44 (115.18)	Not available
Range	112.46–121.14	

Received level values are means with medians in parentheses. Range values are minimum to maximum. Source levels associated with vessel presence are available only for Location 1 because weather necessitated that the DE passenger ferry use a different dock for safety

3.3 Baseline Ambient-Noise Assessment in SC

Baseline ambient received noise levels were documented at four locations in SC. The overall average ambient-noise level was below 118 dB re 1 μPa at 1 m and ranged between 110 and 135 dB re 1 μPa at 1 m. Each monitored site varied slightly in range and average level, with the area adjacent to a boat ramp presenting the loudest ambient-noise levels (139.57 dB re 1 μPa at 1 m). These recordings were collected in advance of a repair-and-renovation construction project.

4 Discussion

4.1 Dolphin Calls Near Bimini

Data were recorded continuously during two 2-weeks periods in August and September 2011 and were examined for the presence of dolphin calls in 2-h increments/day. Early analysis indicates dolphin vocal behavior was detected each day and during each 2-h period but with a pattern possible: from 1,001 to 1,400 h yielded a series of 2 periods with the lowest number of recorded detections (i.e., 8/period). Sighting data (Dolphin Communication Project [DCP], unpublished data, 2003–2012) indicate that the dolphins regularly use the area immediately around the deployment site during the afternoon hours. Dolphins in this area have been observed socializing, playing, traveling, and crater feeding (Melillo et al. 2009; DCP, unpublished data, 2003–2012). Because sighting efforts were skewed to late afternoon and never included postsunset or presunrise times, these PAM recordings marked the first time researchers were able to document the presence of dolphins in the area during the night.

4.2 DE Noise Monitoring

Average noise levels recorded at DE were below the upper limit values proposed by the US National Marine Fisheries Service (NMFS) regulations (160 dB re 1 μPa at 1 m) for confirmed behavioral disturbance related to sound pressure values (Southall et al. 2007). Minimum SPL values were consistent between recording periods while the highest levels were recorded in association with vessel noise. From the RLs, SLs were estimated based on a modified equation for spreading loss. These levels were estimated when a known anthropogenic noise source was identified as present and within range; all estimated SLs were still below limits proposed by the NMFS for behavioral disturbance associated with noise (Southall et al. 2007). It is important to note that vessel activity and associated noise levels under water were only documented for the first two locations because of inclement weather. Wind and wave action was excessive and likely added to the ambient-noise levels documented but eliminated vessel noise during deployments 3–5. Deployment during a period of time when sea and wind conditions were optimal would provide comparative data under standard weather situations with respect to noise levels.

4.3 SC Baseline Ambient Noise

Baseline ambient-noise levels over four 72-h periods remained below 118 dB re 1 μPa at 1 m. Each monitored site varied slightly in range and average ambient-noise level; predictably, areas adjacent to a boat ramp presented the loudest maximum ambient-noise levels. It is likely that these maximum values coincided with vessel traffic, when boats were launching or returning, because they were not consistently documented in the rest of the cove.

4.4 Conclusions

The SM2M recorder was a useful tool in a variety of settings for the purposes of recording both animal and anthropogenic sounds. The data collected via the SM2M unit for SPL values were comparable to recordings obtained with a custom SPL meter. Future data collection could focus more directly on gathering audio and associated-behavior data from free-ranging dolphins while concurrently documenting anthropogenic sounds (e.g., vessel noise) to better understand how dolphin behavior might be impacted from man-made noise.

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Chapter 30
Soundscapes and Larval Settlement: Larval Bivalve Responses to Habitat-Associated Underwater Sounds

David B. Eggleston, Ashlee Lillis, and DelWayne R. Bohnenstiehl

Abstract We quantified the effects of habitat-associated sounds on the settlement response of two species of bivalves with contrasting habitat preferences: (1) *Crassostrea virginicia* (oyster), which prefers to settle on other oysters, and (2) *Mercenaria mercenaria* (clam), which settles on unstructured habitats. Oyster larval settlement in the laboratory was significantly higher when exposed to oyster reef sound compared with either off-reef or no-sound treatments. Clam larval settlement did not vary according to sound treatments. Similar to laboratory results, field experiments showed that oyster larval settlement in "larval housings" suspended above oyster reefs was significantly higher compared with off-reef sites.

Keywords Clams • Estuarine soundscape • Habitat-specific sounds • Larval settlement • Oysters

1 Introduction: Sound as a Settlement Cue

Larval settlement in marine systems can generate significant spatiotemporal variation in the size of open populations, their dynamics, and community structure (Roughgarden et al. 1988; Cowen and Sponaugle 2009). Most marine larvae have very specific settlement habitat requirements that enhance postsettlement growth and survival, and larvae apparently integrate a suite of sensory cues over multiple scales in time and space as they choose a settlement habitat or location (Kingsford et al. 2002; Metaxas and Saunders 2009 and references therein). Unlike strong swimming larvae that can, under certain current conditions, direct their horizontal

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movement in response to environmental stimuli, weak swimmers may respond to settlement cues by vertical movement that facilitates transport to settlement habitat (Kingsford et al. 2002). The better studied environmental cues such as chemicals, biofilms, and near-bottom flow patterns, however, often operate at relatively small spatial scales (centimeters to meters) relative to the scales of larval dispersal and habitat patches (tens of meters to hundreds of kilometers; Turner et al. 1994; Rittschoff et al. 1998). Conversely, sounds associated with settlement habitats can operate over relatively large spatial scales (meters to kilometers) and reflect the quality and characteristics of the source environment (Montgomery et al. 2006; Radford et al. 2008; see Chapter 77 by Lillis et al.).

Soundscapes, the distinct complement of sounds emanating from a particular environment, provide rich sensory information related to the biological and physical characteristics of the source habitat. Biological sources of habitat-specific sounds include soniferous invertebrates, fish, and mammals, whereas physical sources include waves crashing or increased turbulence via currents passing over structured habitats (Montgomery et al. 2006; Kennedy et al. 2010; Radford et al. 2010). There is a growing list of studies that have documented the enhanced settlement of fish and crustacean larvae in response to the sounds of coral reef and rocky shore habitats (e.g., Montgomery et al. 2006; Stanley et al. 2010). For example, certain species of coral reef fish larvae in the field were attracted to sound frequencies specifically associated with coral reefs (Simpson et al. 2008), and a number of coral and rocky reef species of crabs in the laboratory demonstrated enhanced settlement behavior and rates of metamorphosis when exposed to sound from settlement habitats (Stanley et al. 2010).

The marine soundscape is increasingly considered an important sensory cue for marine fish and crustacean larvae (Montgomery et al. 2006), yet the response to ambient habitat sound by nonarthropod invertebrate larvae has only been studied for a single species of coral that was shown to move toward reef sounds (Vermeij et al. 2010). Moreover, the soundscape of estuarine habitats and the response of estuarine invertebrates to such sounds is especially understudied.

2 Conceptual Framework and Study Objectives

The estuarine soundscape is a novel study system in which to investigate sound as a settlement cue for larval organisms, and oyster reefs in particular provide a compelling sonic environment in which to examine habitat-associated sounds and their effect on larval behavior and settlement. Oyster reefs are the required settlement habitat for many reef dwellers with planktonic larvae, yet reefs are, in general, patchily distributed over the scales of larval dispersal (Beck et al. 2011 and references therein). However, because oyster reef habitats support a high density of fish and invertebrates (Boudreaux et al. 2006), many of which are soniferous or create sound through their activity, they produce a distinct reef-related soundscape that is typically far louder than the surrounding areas (see Chapter 77 by Lillis et al.). Extensive soundscape characterization of oyster reef and off-reef habitats in our estuarine system has established that the habitat-associated sounds of oyster reefs could provide appropriate sensory information to larvae seeking settlement habitats and has established the spatiotemporal scales of variation in the soundscape needed to develop a conceptual model of how oyster reef sound could serve to facilitate an encounter with a suitable substrate (see Chapter 77 by Lillis et al.). Therefore, the goal of this study was to evaluate the possibility of sound as a settlement cue for estuarine larvae by investigating the effects of habitat-associated sounds on the settlement response of two species of bivalves with contrasting habitat preferences: (1) *Crassostrea virginicia* (eastern oyster), which prefers to settle on reef-forming conspecifics, and (2) *Mercenaria mercenaria* (hard clam), which settles on a wide range of unstructured habitats.

3 Laboratory Settlement Experiments

Laboratory experiments tested the settlement response of oyster and clam larvae to natural ambient sound associated with oyster reefs versus unstructured soft-bottom as well as a no-sound control (Lillis et al. 2013; A. Lillis, unpublished data). We tested the hypotheses that oyster larval settlement would be higher in the presence of sound associated with their preferred settlement habitat (oyster reefs), whereas clam larval settlement either would be higher in the presence of sound associated with unstructured soft-bottom habitats or would show no response.

Oyster larvae were obtained from the Horn Point Laboratory, University of Maryland, oyster hatchery. Clam larvae were obtained from several commercial hatcheries as available. Before experiments were performed, the larvae were maintained in the laboratory in 10 μm of filtered seawater at salinities matching hatchery rearing conditions and held at room temperature (23–25 °C) for the duration of the trials.

3.1 Sound Treatments

Acoustic treatments used in laboratory larval settlement experiments consisted of replaying habitat sounds recorded in situ at four locations in Pamlico Sound, NC: two oyster reef and two adjacent off-reef soft-bottom habitats. Experimental playback treatment recordings were selected from longer recordings of ambient habitat sound collected from the oyster reefs and nearby soft bottoms (~2 km from oyster reefs) simultaneously over dusk and nighttime periods during new moon (±3 days) periods in the summer and fall months (Lillis et al. 2013). Reef and off-reef habitats had distinct acoustic characteristics (see Chapter 77 by Lillis et al.).

Before the start of the experimental trials, sound treatments that were played via underwater speakers were calibrated and adjusted to reflect typical oyster reef or off-reef sound pressure levels as necessary. Moreover, additional particle acceleration measurements were made following the methods of Glade (1982) and Wahlberg et al. (2008) and verified that the observed particle motion was consistent with that expected under far-field acoustic conditions for measurements made across the 0.5–6-kHz bandwidth (Lillis et al. 2013). Hydrophone recording in the no-sound (control) tanks also confirmed the absence of substantial noise from these treatments (Lillis et al. 2013).

3.2 Oyster and Clam Settlement Trials

For each oyster settlement trial, 15 groups of 100 actively swimming pediveliger larvae were placed in 80-mL clear acrylic containers and randomly assigned to 1 of 3 experimental tanks (5 larval cultures/tank). For clam settlement trials, 6 experimental arenas were available, and 18 groups of actively swimming pediveliger larvae were randomly assigned to containers and tanks (3 larval cultures/tank). Each container had a 3-cm-diameter oyster shell disc as a settlement substrate for the oysters or 100–400-μm-diameter inert glass beads filled to 1-cm depth as a settlement substrate for the clams. All trials were run under complete darkness for 48 h. The experimental tanks were randomly designated as reef sound, off-reef sound, or no-sound treatments before each trial, and for sound treatments, a recording was played continuously for the length of the trial. Oyster settlement at the conclusion of a trial was measured in each container under a dissecting microscope as the proportion of individuals attached to the substrate or container surfaces, and the mean proportional settlement for each replicate was calculated. Clam settlement was determined by siphoning the water in each container to within 1 mm of the substrate surface, counting the number of unsettled individuals, and subtracting them from the 100 total individuals to obtain the proportion settled, to be used to calculate the mean proportional settlement for each replicate.

For both the oyster and clam larval settlement experiments, a randomized block ANOVA was used to test for a difference in the response variable (mean settlement) among sound treatments, blocked by trial. The oyster reef sound treatment consistently enhanced oyster settlement by ~5–10% in each trial compared with the other treatments. The proportional oyster larval settlement was significantly higher when exposed to the reef sound treatment compared with both the off-reef sound and no-sound treatments (randomized block ANOVA: $F_{2,16} = 15.59$, $P < 0.001$; Fig. 30.1). Mean oyster larval settlement for the off-reef sound treatment did not significantly differ from the no-sound treatment (Tukey's honestly significant difference test, $P > 0.05$). Conversely, clam larval settlement did not vary significantly according to any of the sound treatments (randomized block ANOVA: $F_{2,12} = 0.84$, $P = 0.457$; Fig. 30.1).

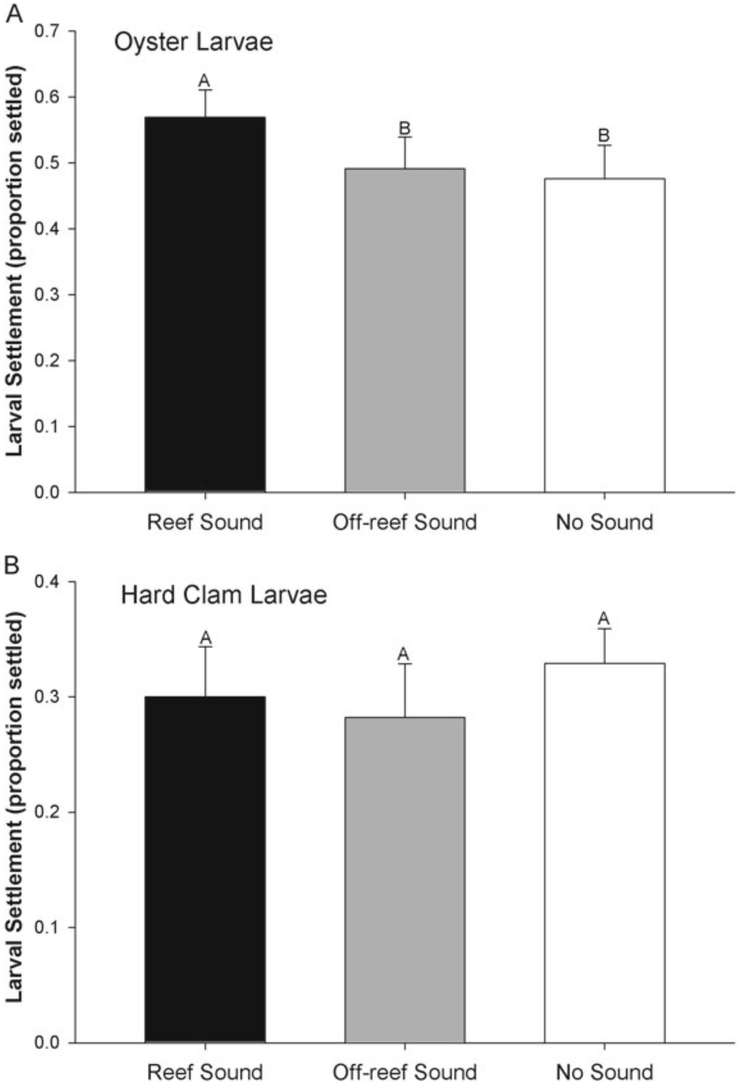

Fig. 30.1 Larval settlement of oysters (*Crassostrea virginica*; (**a**) and clams (*Mercenaria mercenaria*; (**b**) as a function of habitat-specific sound treatments (Reef Sound, Off-reef Sound, and No-sound Control) in laboratory experiments. Values are means + SE. Letters above each histogram denote significant differences between means as revealed by a multiple comparisons test. Adapted from Lillis et al. (2013)

4 Field Settlement Experiments

Because acoustic stimuli matching field conditions are particularly difficult to produce in small laboratory tanks (Au and Hastings 2008), we carried out a field experiment to test if larval settlement was higher in larval cultures anchored in housings above oyster reefs compared with nearby unstructured soft bottoms of the same depth (Lillis et al. 2013). The field experiments for oyster settlement were completed in 2012, and we anticipate completing the clam settlement field experiments in spring 2014.

The field-based experiment was conducted within an oyster reef and the adjacent unstructured bottom area of an embayment in Pamlico Sound, North Carolina, known as West Bay. The oyster reef served as the "reef sound" treatment location, and the "off-reef sound" site was a soft-sediment bottom located ~800–1,000 m from the oyster reef. Previous acoustic surveys to characterize the soundscape of the area consistently demonstrated distinct sound characteristics for the reef versus off-reef habitats as well as a substantially diminished reef sound at a distance of 800–1,000 m from an oyster reef (see Chapter 77 by Lillis et al.). Acoustic measurements made at the study location during the field experiments showed that the sound levels and frequency composition varied between oyster reef and off-reef sites (Lillis et al. 2013). In general, the spectral composition of the reef sound recordings provided a substantial contribution of higher frequency (>1–2-kHz) sounds relative to the off-reef site spectrum, which was dominated by lower frequency sounds.

4.1 *Oyster Settlement Trials*

Four oyster larval settlement trials were completed in June and September 2011 and July and August 2012. In each trial, four replicate "larval housings" were placed at each site (reef vs. off reef) and suspended 1 m above the seabed. Larval housings consisted of acrylic sample jars containing an oyster shell disc as settlement substrate. Corresponding to laboratory settlement experiments, groups of 100 hatchery-reared larvae were placed in the tightly sealed jars before random assignment to a treatment and deployment at the reef and off-reef sites, thereby exposing larvae to habitat sounds while excluding other potential habitat-associated cues such as differences in water chemistry. At the reef site, larval housings were deployed on the sand bottom adjacent to the oyster reef structure to minimize potential differences in light or visual cues between the reef and off-reef habitats. At the conclusion of each 48–72-h trial, larval housings were retrieved by scuba divers and settlement discs were preserved in 95% ethanol. The proportion of larvae attached to the substrate was measured in each culture and used to calculate the response variable, the mean proportional settlement, for each replicate.

A replicated randomized block ANOVA model tested for differences in mean proportional settlement between the habitat sound treatments, with trial as the blocking factor and a block by treatment interaction term. The results of this field experiment agreed with the overall laboratory experiment findings that oyster reef sound increases oyster larval settlement. Oyster larval settlement in larval housings suspended in oyster reef habitats was significantly higher compared with larval settlement in off-reef sites (randomized block ANOVA: $F_{1,24} = 15.13$, $P < 0.001$; Fig. 30.1b), with no significant block by treatment interaction.

5 Conclusions and Future Directions

Manipulative laboratory and field experiments found increased settlement in oyster larvae exposed to oyster reef sound compared with the sound of unstructured soft-bottom or no-sound treatments. Conversely, clam larval settlement did not respond to any of the sound treatments. The results suggest that oyster larvae have the ability to respond to sounds indicative of optimal settlement sites, and this is the first evidence that we are aware of how habitat-related differences in estuarine sounds influence the settlement of a mollusk. What is unclear, however, is why clam larvae showed no response to sound treatments in this study, whereas oyster larvae did.

Differences in life history trade-offs between clams and oysters may explain differences in the larval settlement response of oysters and clams to habitat-specific sound. For example, clams appear to exhibit a more generalist life history strategy whereby they invest in large spawning output and settle in widely available estuarine soft substrates (sand, mud, and gravel; Gosling 2003). Although clam larvae can choose settlement substrates that tend toward larger sediment grain sizes, they often cannot do so under realistic flows (Butman et al. 1988). However, clams are somewhat mobile in their postsettlement life and able to migrate within the substrate (Gosling 2003). Conversely, oyster larvae must locate very patchily distributed hard substrates on which to permanently attach and have evolved the ability to use water-soluble chemical cues to choose appropriate settlement habitats even under realistic current flows (Turner et al. 1994). They have also apparently evolved to detect and respond to the sounds of oyster reefs to possibly help them orient to reefs at relatively large spatial scales associated with dispersal (see Chapter 77 by Lillis et al.). These potential explanations and others will require further testing.

Larval auditory reception is especially unstudied, but documented behavioral responses provide convincing evidence that larval-stage animals can detect sound (e.g., Montgomery et al. 2006), and the presence of statocyst structures in the larval stages of many marine invertebrates suggests that they have this sensory capability (Budelmann 1992). The two primary candidates for marine invertebrate hearing are epidermal cells sensitive to vibration and local water movements and internal statocyst receptor systems (Budelmann 1992). Many bivalve species, including eastern oysters and hard clams, develop statocyst structures in the pediveliger (presettlement) stage (Cragg and Nott 1977), and these mechanosensory receptors are apparently highly sensitive to mechanical waterborne vibrations (Mooney et al. 2010). A third putative hearing structure exists that is particular to bivalve mollusks. The abdominal sense organ (ASO) is a mechanosensory receptor highly sensitive to mechanical waterborne vibrations (Zhadan 2005). It is unknown what mechanosensory receptor(s) is used by oyster larvae. The study of larval mechanoreceptors represents a key area for future investigation in this field.

The importance of underwater sound to a range of ecological processes is only beginning to be discovered (Slabbekoorn and Bouton 2008). Improved understanding of the relationship between habitat sound fields and subsequent larval recruitment is central to biophysical studies of larval connectivity and recruitment in marine systems and the potential adverse effects of noise pollution in the ocean as well as the additional yet untested benefits of marine reserves. Our future work will examine the role of specific sound characteristics on larval behavior and settlement in oysters, quantify the biotic sources of key sound characteristics, and match these important sound characteristics to relevant spatiotemporal scales of sound variation in the estuary (see Chapter 77 by Lillis et al.).

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Chapter 31
Characterizing Marine Soundscapes

Christine Erbe, Robert McCauley, and Alexander Gavrilov

Abstract The study of marine soundscapes is becoming widespread and the amount of data collected is increasing rapidly. Data owners (typically academia, industry, government, and defense) are negotiating data sharing and generating potential for data syntheses, comparative studies, analyses of trends, and large-scale and long-term acoustic ecology research. A problem is the lack of standards and commonly agreed protocols for the recording of marine soundscapes, data analysis, and reporting that make a synthesis and comparison of results difficult. We provide a brief overview of the components in a marine soundscape, the hard- and software tools for recording and analyzing marine soundscapes, and common reporting formats.

Keywords Noise budget • Signal detection • Signal classification • Sound recording

1 Introduction

A soundscape is an acoustic environment consisting of natural sounds (including animal sounds and sounds related to weather) and anthropogenic sounds. Marine soundscapes are increasingly being studied, largely driven by environmental concerns. Onshore, nearshore, and offshore industrial development adds underwater noise to the marine soundscape, which potentially impacts on marine fauna. Passive acoustic monitoring is a common tool for the monitoring of marine soundscapes, the assessment of anthropogenic noise and its impacts, and the study of marine animals. Acoustic ecology, the study of the relationship mediated through sound between organisms and between organisms and their environment, is a growing field in the marine sciences. The International Quiet Ocean Experiment (IQOE; Boyd et al. 2011) is an initiative driven by the Scientific Committee on Oceanic

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Research (SCOR) and the Partnership for Observation of the Global Oceans (POGO) and proposes (1) the temporary and local quieting of anthropogenic sound sources in busy regions to assess natural levels of background noise and to study the acoustic ecology of resident animals in natural levels of background noise, (2) the identification and study of sites that have similar characteristics except for their level of anthropogenic noise, and (3) the study of marine soundscapes and acoustic ecology in regions that are still devoid of anthropogenic noise but are expected to change rapidly (e.g., the Arctic). Marine soundscapes are not static but vary naturally over time. Consistent changes in time (trends) have been observed at some northern hemisphere locations and are attributed to increased (distant) shipping (Andrew et al. 2002; Chapman and Price 2011).

Hardware and software tools to study marine soundscapes are widely accessible, available from an increasing number of suppliers, and becoming more and more affordable, to the point where some of the software tools are available as free shareware. However, there are currently no standards for the measurement, analysis, or reporting of acoustic data from marine soundscapes, making it difficult to judge and compare the results. This article aims to give a brief overview of the various aspects and steps involved in the characterization of marine soundscapes.

2 Contributors to the Marine Soundscape

The marine soundscape consists of natural physical sounds (e.g., generated by rain, wind, waves, subsea seismic activity, and ice breakup and ridging), biological sounds (e.g., from cetaceans, fish, and crustaceans), and anthropogenic sounds (e.g., from vessels, sonars, offshore exploration, and construction). “Ambient noise” usually refers to the background level in a soundscape and can include physical, biological, and anthropogenic sources. Wind-driven noise is an example of physical ambient noise. Biological ambient noise includes fish or snapping shrimp choruses, when individual calls and callers cannot be identified, but all calls overlap to create a background din. Distant shipping contributes to ambient noise, particularly in the northern hemisphere; individual ships cannot be detected in the traffic background. Wenz (1962) reviewed several studies on ambient noise and published spectra (graphs of energy versus frequency) of ambient noise in the frequency range from 1 Hz to 20 kHz. The contributions of various sources to the ambient noise vary in time and space. In some areas, ambient ship noise can dominate between 10 and 1,000 Hz. Wind-driven noise often dominates between 50 Hz and 20 kHz. In tropical waters, biological choruses tend to dominate at certain times of the day at frequencies between a few 10s of hertz and 20 kHz (Cato 1978, 1980). Cato (2008) compared the spectra of wind-dependent ambient noise, biological choruses, and traffic noise around Australia.

The acoustic characteristics of individual acoustic events that can be detected in ambient noise have been described and reviewed by many authors. Richardson et al.

(1995) summarized the characteristics of sounds produced by marine mammals and anthropogenic sources. Erbe (2012) compiled a summary plot of source spectra of anthropogenic sound.

The marine soundscape not only depends on sound sources in the surrounding area and their spectra but also on sound transmission parameters. The hydro- and geoacoustic properties of the environment will determine how energy at the various frequencies propagates. Energy in certain frequency bands might attenuate very rapidly with distance. Therefore, a soundscape that, as an example, is dominated by broadband wind-driven noise might show distinct peaks and troughs in its average spectrum, which could falsely be attributed to band-limited sources. It is important to understand the site-specific sound propagation before discussing the shape of soundscape spectra.

3 Recording Marine Soundscapes

Marine soundscapes are recorded with hydrophones, the deployment scheme of which can cause artifacts in the recording. These include flow noise over the hydrophone and mooring; the strumming of mooring lines; the banging of chains or shackles; the sound of waves splashing against the boat and sounds on the boat, if the hydrophone is deployed from a boat; the sound of the hydrophone knocking or moving against the mooring or seafloor; or the sound of sand swishing over the hydrophone, if deployed on the seafloor in shallow water. Turbulence in the ocean and vortices generated at moorings cause local pressure fluctuations that are sensed by the hydrophone and that can far exceed the pressure amplitude in a propagating acoustic wave at low frequencies. Animals crawling over or biting into the hydrophone (as seen from shark teeth stuck in hydrophones) also generate noise artifacts. Specifically, in shallow, tropical waters, moorings create artificial reefs, attracting animals. Data from long-term deployments off the Western Australian coast often show steadily increasing levels of snapping shrimp sound over the course of a deployment. When moorings and hydrophones are retrieved and cleaned from biofouling and redeployed, this noise is "reset" and the settling and associated increase in noise begin again. These sounds are not part of the general soundscape because they would not be present if the hydrophone mooring was absent.

Systems for passive acoustic monitoring and deployment considerations were reviewed by Dudzinski et al. (2011). We find that hydrophone deployments from a boat create a lot of artifacts and that freely drifting systems and systems moored near the seafloor tend to yield better recordings (Erbe et al. 2013).

In an attempt to characterize and quantify marine soundscapes, short-term spot measurements give an instantaneous picture but cannot present the temporal variability, which can be in excess of 20–30 dB over the course of a day and/or season (Erbe and McPherson 2012). Long-term recordings allow a more complete assessment of the marine soundscape.

4 Analyzing Marine Soundscapes

To check and analyze underwater acoustic recordings, a trained acoustician typically listens to the sound and visually inspects its spectrograms (plots of acoustic power as a function of frequency and time). Automatic signal detection and classification algorithms are employed to aid, in particular, the analysis of long-term recordings. Signal detection can be performed by matched filtering and spectrogram correlation (Stafford et al. 1998; Mellinger and Clark 2000) or neural networks (Erbe 2000) if clear examples of the signals to be detected are available beforehand. Most algorithms are based on the computation of a specific quantity $q(t)$ (e.g., energy or kurtosis; Gervaise et al. 2010) and subsequent peak detection. If the instantaneous $q(t)$ surpasses its long-term mean $\overline{q}(t)$ by a multiple i of the standard deviation σ, a signal is deemed present: $q(t) > \overline{q}(t) + i\sigma$. Many of these algorithms have been tuned to detect specific signals (e.g., calls from a specific animal) in specific environments. Algorithms that can detect a variety of signals under variable ambient noise conditions remain a challenge. Within the framework of a project to synthesize 15 years of sea noise recordings off Western Australia, our approach consists of three detectors: (1) a click detector based on Teager-Kaiser energy (Dimitriadis et al. 2009) that finds very short transient sounds, (2) an entropy-based detector for frequency-modulated signals, and (3) a mean-spectrum shape tracker for long constant-wave sounds such as dredging tonals and fish choruses, which looks at persistent changes (in hours) in the shape of the spectrum. The entropy detector is a 2-D version (operating on time-frequency bins) of the earlier 1-D version (Erbe and King 2008), which operated on frequency only. Conceptually, the power spectrogram is transformed into an entropy surface, which highlights areas within the spectrogram that are unpredictable. Regions of unstructured noise have high entropy (close to 1); regions with embedded signals have low entropy (close to 0). Applying a threshold to the entropy surface yields the shape of the underlying signal in the spectrogram.

Once potential signals are detected, the following algorithms have been employed for their classification: feature extraction followed by discriminant function analysis (Baumann-Pickering et al. 2010), classification and regression tree analysis (Oswald et al. 2007), neural networks (Thode et al. 2012), dynamic time warping, useful for the classification of calls with changing duration (Brown and Miller 2007), hidden Markov and Gaussian mixture models (Brown and Smaragdis 2009), and some others. Having detected and classified specific sounds in the soundscape, the latter can be characterized and quantified.

5 Describing and Quantifying Marine Soundscapes

Soundscapes are commonly displayed as spectrograms. Spectrograms loosely portray the way we hear, they show how a soundscape changes with time and frequency, and they are conceptually very easy to understand. Acoustic events can be highlighted in spectrograms, making them very attractive for presentation to

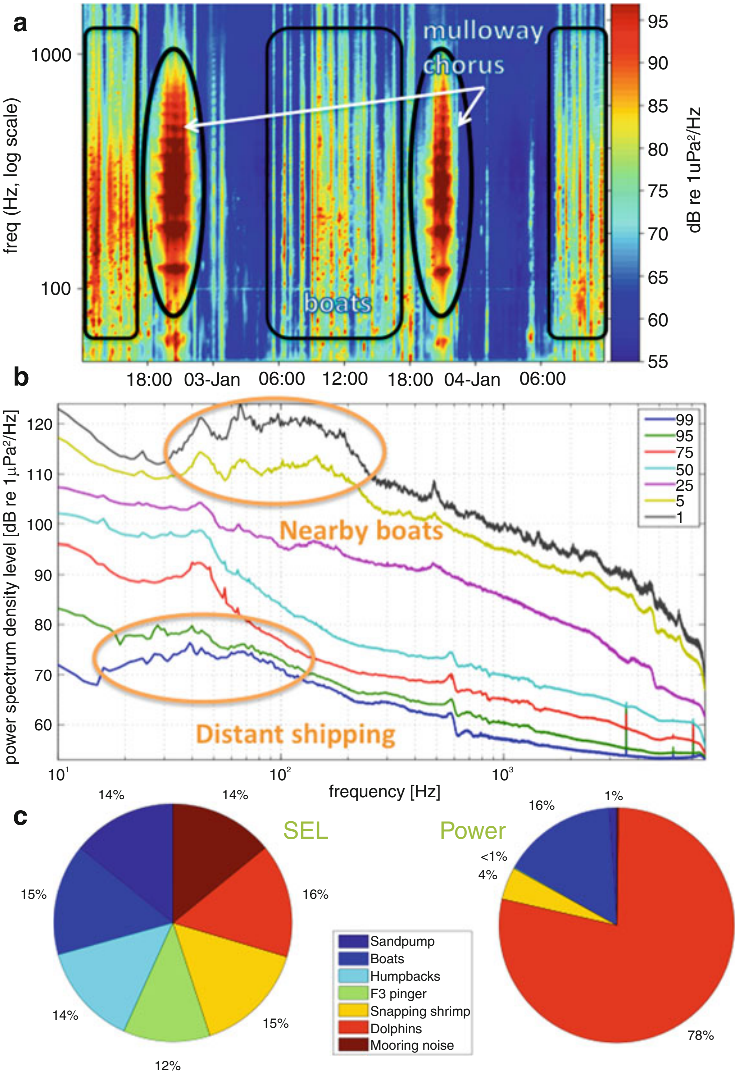

Fig. 31.1 (**a**) Sample spectrogram of 48 h of the marine soundscape off Perth, Western Australia, January 2006. (**b**) Power spectrum density percentiles of the marine soundscape off Haida Gwaii, Canada, July 2010. (**c**) Noise budgets for a 24-h period off Queensland, Australia, September 2010. *Left*: sound exposure level (SEL) computed over a 24-h period; *right*: power

nonacousticians (see Fig. 31.1a). Spectrograms are "calibrated" and typically displayed in units of power spectrum density (in µPa²/Hz). Although spectrograms are commonly used to display signals in recordings of a few seconds, minutes, or hours length, they are not useful for displaying long-term recordings over months and years. In this case, power spectrum density percentile plots are preferable (see Fig. 31.1b). These show the statistical distribution of energy with frequency. The *n*th percentile gives the level that is exceeded *n*% of the time. Computation of 95th, 75th, 50th, 25th, and 5th percentiles is common. The 50th percentile is equal to the median spectrum.

A representation increasingly seen is that of noise budgets in the form of pie charts, where each contributor to the soundscape gets assigned a pie segment depending on the "level" contributed to the soundscape. These pie charts can be very misleading. The relative sizes of the pie segments vary depending on the quantity plotted (e.g., energy or power), the scale (linear versus logarithmic), and the bandwidth (Erbe and McPherson 2012). In Fig. 31.1c, the various sound sources contributed fairly evenly in terms of sound exposure level (SEL) over a 24-h period. In terms of acoustic power received at the hydrophone, dolphins, even though they were only present for a total of 1 h, produced the highest level because of their proximity to the hydrophone. Boat passes were few but close, hence their large contribution as well. While pingers were heard every 4 s for 24 h, their received level was low at this site. Integrated over 24 h, they contributed an even share to the soundscape in terms of SEL, but the received power was low.

6 Conclusions

The increasing interest in and funding for research on marine soundscapes is important for the sustainable management of the marine environment. With a decrease in equipment cost, analysis tools becoming shareware, and data being freely available online from ocean observatories, the potential for acoustic ecology studies is growing. However, the quality of the results cannot be ascertained until common protocols or standards are developed for the collection, analysis, and reporting of acoustic data.

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Chapter 32
Pile-Driving Noise Impairs Antipredator Behavior of the European Sea Bass *Dicentrarchus labrax*

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Abstract In an increasingly industrialized world, man-made noise is changing the underwater acoustic environment. The effects of anthropogenic noise on marine ecosystems are not yet fully understood despite important implications for science and policy, in particular with respect to investment in offshore renewable energy. In this study, a traditional looming-stimulus experimental setup was used to investigate the acute effects of pile-driving noise on the antipredator response of European sea bass (*Dicentrarchus labrax*). Playback of pile-driving noise was found to impair significantly the startle response of individuals, which potentially translates to an increased likelihood of being captured by predators in natural conditions.

Keywords Looming stimulus • Startle response • Survival • Fitness consequences

1 Introduction

Anthropogenic noise levels in the marine environment have increased substantially since the Industrial Revolution and the potential consequences for marine life are of international concern. Pile driving is often the predominant source of underwater noise around the UK coast due to the increasing construction of offshore wind, wave, and tidal installations. These installations provide a crucial element of the UK's response to the need to reduce CO_2 emissions and ensure energy security and, under the European Commission Marine Strategy Framework Directive, noise must now be monitored and managed. It has been suggested by the UK Crown Estate that as a result of the uncertainty surrounding the impacts of noise on aquatic life, 75%

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of wind farm developments are currently at risk of not being built, with implications for the UK economy and industries.

Sound from pile driving and many other human activities is generally low frequency, falling within the hearing range of many fish species (Slabbekoorn et al. 2010). The European sea bass (*Dicentrarchus labrax*) is a commercially important species in many Atlantic and Mediterranean countries, including the UK, both for capture fisheries and increasingly for aquaculture. Little is known about the effects of noise on *D. labrax* despite the potential conflict between the fishing and offshore renewable energy industries.

This study examined the effect of playback of pile-driving noise on the antipredator response of *D. labrax*, providing a measure of an ecologically important behavior that has direct implications for survival. A predator attack was simulated using a looming stimulus (Fuiman and Cowan 2003) to test the hypothesis that antipredator behavior would be altered in fish exposed to playback of pile-driving noise relative to those exposed to ambient harbor noise. We hypothesized that pile-driving noise may either (1) reduce the proportion of fish that startle, with or without an effect on response time, due to stress and/or distraction or (2) increase the proportion that startle due to a heightened state of alert induced by stress.

2 Materials and Methods

2.1 Noise Treatments

Recordings from three UK harbors (Portsmouth, Plymouth, and Gravesend) were used to create ambient noise tracks (three per harbor) and these were combined with three recordings of pile-driving noise to create nine harbor + pile-driving noise tracks (henceforth called pile driving). Thus, to minimize pseudoreplication in the experiment, we used 18 unique experimental tracks in a blocked design, with half of the fish tested in ambient-noise playback and half in pile-driving conditions. The recordings were made using a calibrated omnidirectional hydrophone (HiTech HTI-96-MIN with inbuilt preamplifier, High Tech, Inc., Gulfport, MS) and an Edirol R09-HR 24-Bit recorder (44.1 kHz sampling rate, Roland Systems Group, Bellingham, WA). The recording level was calibrated for the R09-HR using pure sine wave signals, measured in-line with an oscilloscope, produced by a function generator. Experimental tracks were created using the open source audio editor Audacity (http://audacity.sourceforge.net/) and were repeated to create tracks that were a standard 30 min. The WAV sound files were played back via a sound system consisting of a battery (12 V 7.2 Ah sealed lead-acid), WAV/MP3 player (Philips GoGear VIBE, Koninklijke Philips NV, Amsterdam, The Netherlands), and amplifier (M033N, 18 W, frequency response: 40–20,000 Hz; Kemo-Electronic GmbH, Langen, Germany) attached to an underwater speaker (Lubell Labs University Sound UW-30, frequency response 100–10,000 Hz; University Sound, Columbus, OH).

This is the same basic procedure and setup used in previous studies investigating the effects of sound on behavior (Bruintjes and Radford 2013; Wale et al. 2013a, b).

There was no fade in or fade out to the track because pile-driving noise has a sudden onset. Noise in the glass experimental tank was measured during playback of ambient and pile-driving tracks using a calibrated hydrophone. The hydrophone was placed inside the plastic container used to contain each fish during the experiments to ensure that the noise recorded was the same as the noise experienced by the fish. Before the experiment was started, playback recordings were analyzed in Avisoft SASLab Pro v.4.52 (Avisoft Bioacoustics, Berlin, Germany) and then adjusted in Audacity (http://audacity.sourceforge.net) to achieve uniform sound levels between the nine pile-driving tracks and between the nine ambient tracks. The average peak sound level of the pile-driving tracks (averaged from 1-s recordings during pile strikes) was 160.5 ± 0.1 dB root-mean-square (rms) re 1 μPa and the average sound level of the ambient tracks (averaged from 10-s recordings) was 123.2 ± 0.1 dB rms re 1 μPa.

Averaged power spectra were calculated using a fast Fourier transform (FFT) analysis (spectrum level units normalized to 1-Hz bandwidth; Hann evaluation window, 50% overlap; FFT size 1024). For comparative purposes, an ambient track from harbor A (power spectrum averaged from 5-s recordings) is displayed alongside a pile-driving track (power spectrum averaged from 1-s recordings during pile strikes) in Fig. 32.1. Like most fish, *D. labrax* will detect the particle motion element of sound but because they have a swim bladder, they are also likely to be sensitive to changes in pressure. For logistical reasons, we report the sound pressure levels of the playback of tracks for comparison between pile-driving and ambient control conditions (Radford et al. 2012).

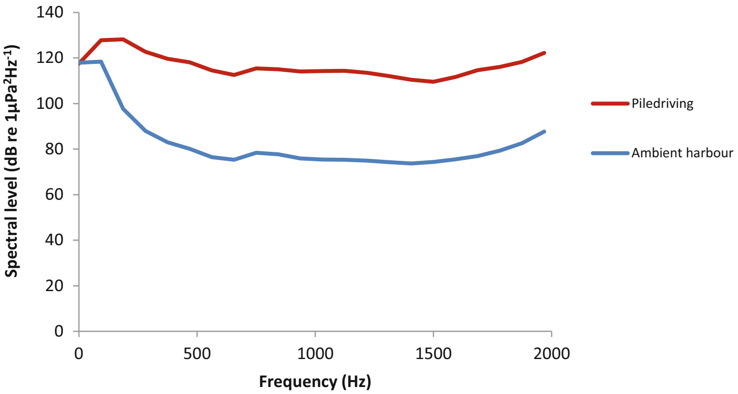

Fig. 32.1 Playback of ambient and pile-driving noise in the experimental tank. Spectral level of ambient and pile-driving tracks from averaged power spectra (fast Fourier transform [FFT] analysis: spectrum level units; Hann evaluation window, 50% overlap; FFT size 1024) recorded in the experimental tank

2.2 Experimental Protocol

Juvenile *D. labrax* were sourced from an aquaculture facility, housed in the Aquatic Resource Centre at the University of Exeter at 16.5 °C, and fed a combined diet of pellets and live *Artemia* several times a day. A total of 36 fish were used in the experiment, with 18 tested during pile-driving noise and 18 tested during ambient harbor noise. The test subjects had not been used in previous experiments and were not reused within the experiment, ensuring that all subjects were naïve to the looming stimulus. Trial order and use of tracks from different harbors were counterbalanced within each block and treatments alternated between ambient harbor noise playback and pile-driving noise playback.

In each trial, a fish was transferred to a small plastic container (15 cm length × 10 cm width × 10 cm depth) using a scoop and allowed to acclimatize for 5 min with the lid off to avoid oxygen depletion. The ambient track was then started in the experimental tank (55 cm length × 45 cm width × 45 cm depth with a water depth of 35 cm) and the container with the lid on was placed close to the edge inside the tank. All the fish experienced 2 min of ambient-noise playback while settling, after which the track was switched either to a different ambient track or to a pile-driving track and the looming predator stimulus was released 10 s later. The looming stimulus consisted of a black squash ball threaded onto thin fishing line to mimic the open mouth of a predator. The release of the squash ball was controlled using a simple mechanism that was not visible to the fish, and the ball was set up so that it swung directly toward the fish but was restrained by a lanyard to avoid hitting the tank. After the trials, the fish were returned to a separate holding tank, the plastic container was washed, and the water was refreshed before the next trial.

Experiments were filmed using a video camera mounted on a tripod at the side of the tank. The experimenter was hidden from the fish by a hide, which was positioned in a way that ensured that the movements to start and stop recording were not visible to the fish. The underwater speaker was placed in the center of the tank under a false bottom, facing upward, with the container with the fish placed above. To minimize vibrations, the tank was placed on top of 5 cm of expanded insulation foam. The entire setup was surrounded by an opaque partition divider to block out external disturbances.

2.3 Statistical Analysis

Trial videos were exported to a PC and analyzed in Windows Media Player at 25 fps with the sound switched off to eliminate observer effects. Each fish was scored for a C-start type of startle response to the looming stimulus, and for those that startled, the lag response time from the "predator" beginning to move to the fish eliciting a response was measured. Data were analyzed using SPSS (version 10). A χ^2 test was used to determine whether the number of fish that exhibited a startle response was significantly different between the control group and the group exposed to playback of pile-driving noise. An independent-samples *t*-test was used to compare the lag response times between fish from the two treatment groups that did startle.

3 Results

Antipredator behavior was impaired in *D. labrax* subjected to a simulated predator attack when pile-driving noise was playing. During pile-driving noise playback, fish were significantly less likely to startle in response to the looming stimulus compared with those experiencing an attack during ambient harbor noise playback ($\chi^2 = 5.46$, df = 1, $n = 36$, $P = 0.019$; Fig. 32.2). Of the fish that startled, there was no significant difference in response time to the "predator" between those experiencing ambient harbor noise playback and those experiencing pile-driving noise playback (independent-samples *t*-test, equal variances not assumed: $t = 1.91$, df = 4.25, $n = 17$ [12 in ambient, 5 in pile driving], $P = 0.125$).

4 Discussion

Antipredator responses are of ecological importance for any animal in determining survival, yet to date little experimental work has considered the impact of anthropogenic noise in this regard. Notable exceptions to this shortfall in the literature include recent work by Chan et al. (2010), Bruintjes and Radford (2013), and Wale et al. (2013a). The startle response is crucial in avoiding attacks from ambush predators so any stressor that impairs this response likely reduces an individual's chance of survival. In this study, playback of pile-driving noise significantly reduced the number of individuals that startled during a simulated attack. This suggests that

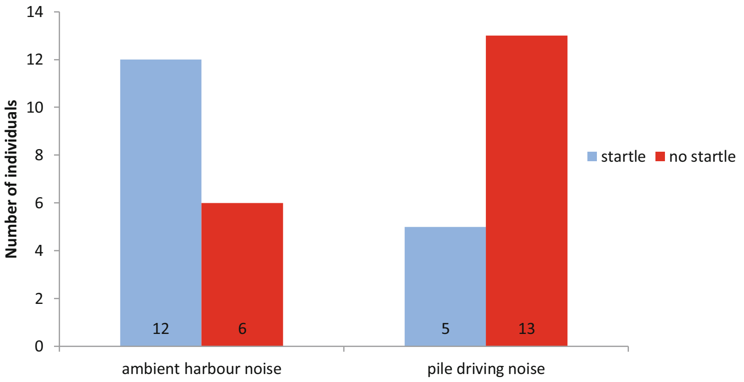

Fig. 32.2 Startle response of *Dicentrarchus labrax* during playback of ambient harbor noise or pile-driving noise ($n = 18$ for each treatment)

D. labrax are more vulnerable to predation when experiencing playback of pile-driving noise, although it may also be the case that in natural conditions pile-driving noise also impacts the strike efficiency of the predator. Thus, the possible effects of pile-driving noise on natural predators also need to be understood to gain better insight into the overall impact of pile driving on predator–prey interactions. If pile-driving noise is also detrimental to the natural predators of *D. labrax*, then the impact of impaired antipredator behavior may be reduced.

Further research is needed to determine the effects of pile-driving noise on other aspects of fish behavior and physiology. It is important to consider the implications of other effects in conjunction with impaired antipredator behavior to provide a perspective of the "big picture." Change in antipredator behavior is likely one facet of an allostatic response and so it is not enough to assess the effects of pile-driving noise on antipredator behavior in isolation. For example, Simpson et al. (2014) have found that eels exposed to ship-noise playback increase their oxygen consumption and, as a consequence, their energetic demands. If this is also true of *D. labrax*, then they would need to increase the time spent foraging to fulfil their higher energy expenditure while also being more vulnerable to predators.

The mechanism responsible for the reduction in the number of individuals that startled is not known but may be a consequence of stress and/or distraction. Stress may impair the ability of fish to detect and classify predators (Wright et al. 2007). Furthermore, if repeated exposure of pile-driving noise results in chronic stress, then there will likely be significant effects on metabolism, growth, and, ultimately, reproductive fitness (Kight and Swaddle 2011). If attention is narrowed, with fish either ignoring stimuli or focusing on a smaller spatial scale, then predators may be less likely to be detected. Such attention-mediated effects are driven by a limited capacity to attend simultaneously to multiple stimuli (Chan and Blumstein 2011).

The effects of pile-driving noise on antipredator behavior discussed in this paper may be conservative estimates because sound levels nearer the source can be as loud as 205 dB re 1 μPa (Bailey et al. 2010). However, in the open ocean, fish may move away from pile-driving noise to minimize its impact on their behavior and physiology. It is likely that as fish move away from the source, the sound will get less intense and have a smaller effect, but if fish remain significantly impacted over large distances from the pile-driving operation, then fish populations could be affected. It is uncertain how intense pile driving needs to be to compromise antipredator behavior and this is a valuable question for further research. Avoidance behavior could be detrimental to important breeding or feeding grounds close to sites of offshore construction (Slabbekoorn et al. 2010). If fish are unable to access breeding grounds, there will be negative repercussions for recruitment to fisheries in future years.

In this experiment, *D. labrax* were exposed to 10 s of pile-driving noise playback. Further research is needed to determine whether the effect seen on antipredator behavior is a temporary response to the sudden onset of the noise source. It has yet to be tested whether habituation or sensitization may occur and whether fish show an immediate or gradual recovery at the cessation of exposure; these are important future considerations (see Chapter 111 by Radford et al.).

This study demonstrates that pile-driving noise has the potential to negatively affect the antipredator behavior of *D. labrax* that, if true in natural conditions, would increase the likelihood that individuals will suffer mortality from predation. Further studies are needed to determine the full impact of pile driving on inter- and intraspecific interactions and its potential to disrupt complex interactions within ecosystems.

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Chapter 33
Using Reaction Time and Equal Latency Contours to Derive Auditory Weighting Functions in Sea Lions and Dolphins

James J. Finneran, Jason Mulsow, and Carolyn E. Schlundt

Abstract Subjective loudness measurements are used to create equal-loudness contours and auditory weighting functions for human noise-mitigation criteria; however, comparable direct measurements of subjective loudness with animal subjects are difficult to conduct. In this study, simple reaction time to pure tones was measured as a proxy for subjective loudness in a *Tursiops truncatus* and *Zalophus californianus*. Contours fit to equal reaction-time curves were then used to estimate the shapes of auditory weighting functions.

Keywords Hearing • Loudness • Reaction time • Weighting function

1 Introduction

There has been a great deal of interest in designing criteria for mitigating the effects of anthropogenic noise on marine mammal hearing (e.g., Southall et al. 2007). One of the primary focus areas has been the generation of auditory weighting functions similar to those designed for humans, such as the A-weighting function that is based on the 40-phon equal-loudness contour (American National Standards Institute [ANSI] 1996). These functions allow noise levels to be weighted based on

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the sensitivity of the auditory system as a function of frequency. Generation of weighting functions has typically relied on the derivation of equal-loudness curves, which describe the levels at which sounds of different frequencies are perceived as being equally loud. Equal-loudness curves are typically obtained from loudness comparison tests in which subjects indicate the physical amplitudes of tones of different frequency that are perceived as equally loud (Fletcher and Munson 1933; Suzuki and Takeshima 2004). Such data have been obtained for a *Tursiops truncatus* (Atlantic bottlenose dolphin; Finneran and Schlundt 2011); however, the levels of instruction that are required for subjects to perform these tasks make comparable studies impractical for all but a very small number of species and individuals.

Animal studies have therefore focused on using a correlate of loudness, reaction time (RT), for describing subjective loudness perception (e.g., Stebbins 1966; Green 1975; Pfingst et al. 1975; Ridgway and Carder 2000). Experimental methods for these studies typically require a subject to present a conditioned response on the detection of a pure-tone stimulus. Subject RTs are measured across a range of stimulus sound pressure levels (SPLs) to create RT-SPL functions. These functions have the shortest median RTs at the highest SPLs, and median RT increases exponentially near threshold. Comparison of frequency-specific RT-SPL functions yields "equal-latency" curves that approximate equal-loudness curves (Pfingst et al. 1975).

In this study, RTs are measured in a pure-tone detection task with two marine mammal species: *Zalophus californianus* (California sea lion) and *Tursiops truncatus*. Frequency-specific RT-SPL curves are used to generate equal-latency curves for both species. These curves provide information that can be used to design weighting functions aimed at predicting and mitigating the effects of anthropogenic noise exposure.

2 Methods

2.1 Subjects

The subjects of the study were a 4-year-old male *Zalophus californianus* (subject code JFN) and a 20-year-old male *Tursiops truncatus* (subject TRO) at the US Navy Marine Mammal Program (MMP) in San Diego, CA. Both subjects had full ranges of hearing (characteristic of their respective species) based on previously measured psychophysical hearing thresholds.

2.2 Test Environments and Materials

The *Zalophus californianus* was tested in a sound-attenuating hut located on floating docks in San Diego Bay near the subject's home enclosure (Mulsow et al. 2011). A polyvinylchloride (PVC) experimental apparatus was located inside the hut and had a station where the subject placed his head with a response paddle immediately to his right. The station was equipped with a switch that indicated the moment the subject moved his head to touch the response paddle. A light was placed in front of the subject and was used to delineate the durations of individual trials. Two trainers accompanied the subject into the enclosure. The trainers placed the headphones used for stimulus production on the subject and delivered food reinforcement for correct responses. The experimenter was located in a building adjacent to the sound-attenuating hut. A video camera and headset system allowed the experimenter to monitor events in the sound-attenuating hut and keep in verbal contact with one of the trainers.

The experimenter controlled trials using a desktop computer, a National Instruments PCI-6251 data-acquisition card, and custom LabVIEW-based software (Finneran 2003). Stimuli were 500-ms pure tones (5-ms rise/fall time) with frequencies ranging from 0.125 to 32 kHz in octave steps, delivered to Sennheiser HDA 200 headphones after filtering and attenuation with custom hardware.

Testing with the *Tursiops truncatus* was conducted in an aboveground pool (Finneran et al. 2010). The PVC experimental apparatus included an underwater bite plate on which the subject stationed for each trial. A trial light was placed in front of the subject to indicate the duration of trials. A trainer attended to the subject from a deck above the pool during experimental sessions and delivered food reinforcement for correct responses. The experimenter, located in a separate room next to the pool, monitored the subject using a video camera and kept in verbal contact with the trainer using a headset system.

Acoustic stimuli for the *Tursiops truncatus* were 10% frequency-modulated (FM) tones. The use of frequency modulation reduces variability in the underwater sound field due to multipath interactions and result in hearing thresholds that are comparable to those obtained using pure tones with *Tursiops truncatus* (Finneran and Schlundt 2007). The FM tones were 500 ms in duration (5-ms rise/fall time) with frequencies between 5 and 134.5 kHz. After filtering and attenuation, the tones were presented using an International Transducer Corporation (ITC) 5,446 or 1,032 transducer located in front of the subject.

2.3 Experimental Procedure

Stimuli were presented using a method of constant stimuli and a go/no-go paradigm for both the *Z. californianus* and the *T. truncatus*. At the beginning of a trial, the light in front of the subject was turned on. Two types of trials were possible: signal trials containing an acoustic signal and control trials that were identical to signal trials except for the presentation of an acoustic signal. The occurrence of control trials was random based on conditional probabilities of 0.35 and 0.12 for the *Z. californianus* and the *T. truncatus*, respectively. Each experimental session comprised testing at a single frequency. After a 10-trial "warm-up" at suprathreshold levels, signal levels were chosen at random from a set of sub- and suprathreshold SPLs (in 5-dB increments) on a trial-to-trial basis.

Each species provided a conditioned response on detection of a signal: the *Z. californianus* pressed the response paddle with his muzzle and the *T. truncatus* provided a conditioned phonation (a "burst pulse"). Both species withheld response if no signal was detected. Correct responses (i.e., correctly responding after the presentation of a signal and withholding response in the absence of a signal) were rewarded with a piece of fish delivered by a trainer. Correct detections and rejections were rewarded equally, and in incorrect trials, each species was recalled to the trainer without a fish reward. One (*T. truncatus*) or two (*Z. californianus*) sessions, comprising 100–160 trials, were typically conducted each day, 5 days/week.

3 Data Analysis

Subject RTs were defined as the latency of each subject's response relative to the onset of the signal. The RTs were pooled according stimulus frequency and level. Median RT was then determined for each frequency and plotted as a function of stimulus SPL. The RT-SPL curves were then fit using a Piéron function (Piéron 1952) with the following form

$$\left(RT - t_0\right) = \beta I^{-\alpha} \tag{33.1}$$

where t_0 is the minimum RT at the highest signal levels, β is a free parameter, and α is an exponent. Equal-latency curves were generated by determining the SPLs at each frequency that resulted in equal RTs based on the Piéron curve fits of RT-SPL curves.

4 Preliminary Results

The shortest RTs, found at the highest signal SPLs, were on the order of 200 and 300 ms for the *Z. californianus* and the *T. truncatus*, respectively. Median RT increased with decreasing SPL at all frequencies for both subjects. Increased variability in RTs at near-threshold SPLs was also evident across all tested frequencies for both subjects. These patterns are apparent in the representative RT histograms shown for the *Z. californianus* in Fig. 33.1. Examples of preliminary RT-SPL curves for the subjects are shown in Fig. 33.2. Piéron functions provided a good fit of the RT-SPL data for both subjects. The 300-ms equal-latency curve, based on the Piéron function fit of the *Z. californianus*, was very similar to a behavioral audiogram previously reported for JFN (Mulsow et al. 2011). The curves generated from shorter latencies of 210 and 230 ms were elevated above this audiogram and had a similar shape, although there were some changes relative to the audiogram as a result of relatively rapid increases in RT with decreasing SPL at 0.5 and 8 kHz.

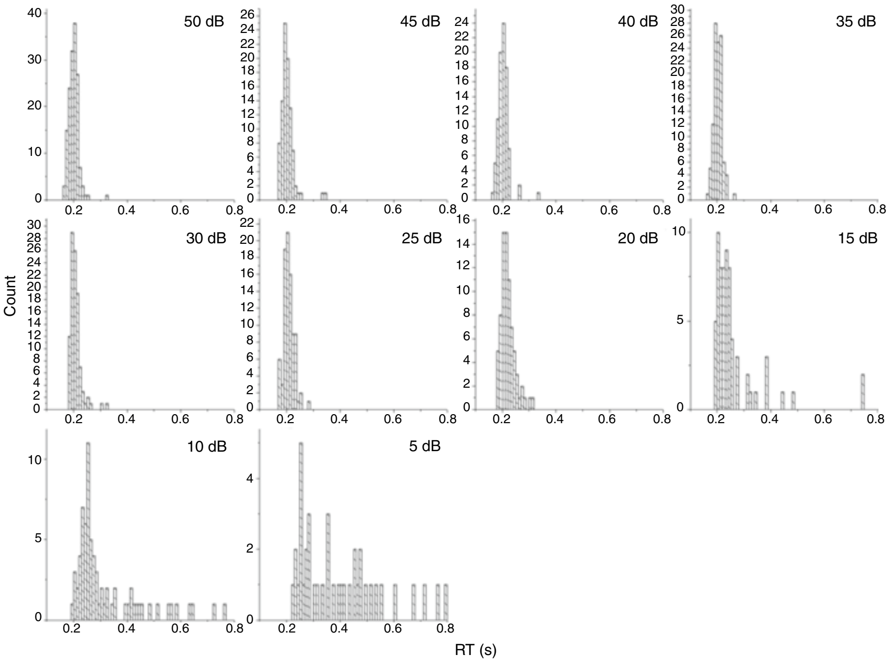

Fig. 33.1 Histograms of reaction-time (RT) data at 8 kHz for a *Zalophus californianus*. The RTs are the shortest and display relatively little variability at the highest levels (in dB re 20 µPa). Fewer replicates are present at the lowest levels because the subject correctly detected fewer signals near threshold

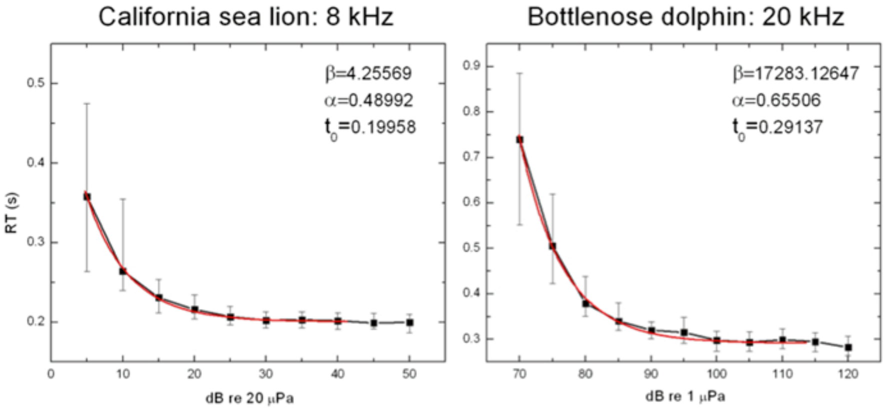

Fig. 33.2 RT-sound pressure level (SPL) curves (*black lines*) and Piéron function fits (*red lines*) for the *Zalophus californianus* at 8 kHz (*left*) and the *Tursiops truncatus* at 20 kHz (*right*). Values are median RTs ± SD at each stimulus level. Values at upper right are the parameters of the Piéron function fits. Piéron functions were fit simultaneously with preliminary data at other frequencies using a shared minimum response-time parameter (t_0). *B* free parameter, α an exponent

5 Discussion

The patterns of increasing median response time with decreasing signal SPL and increased variability at near-threshold SPLs for both subjects are consistent with patterns previously observed with other animal species in similar tasks (e.g., Stebbins 1966; Green 1975; Pfingst et al. 1975). Based on the similarity of these patterns, it can be assumed that the median RT in the current study acts as a proxy for subjective loudness. Preliminary results with the *Z. californianus* suggest that, at least for levels within ~25 dB of threshold, the equal-latency curves (and therefore equal-loudness curves) have a shape that is generally similar to the audiogram. At these low-to-moderate levels, weighting functions for this species may likely resemble an inverted audiogram in shape.

In terms of SPLs that are well above threshold, one of the main concerns with the use of RT as a proxy for loudness is the fact that subjective loudness continues to grow, whereas the RT reaches an asymptote. When generating equal-latency curves from Piéron fits of RT-SPL data, the asymptotic nature of RTs poses a problem. Specifically, when RTs near asymptote (i.e., near t_0) are used to generate equal-latency curves, small changes in RT result in very large changes in the corresponding SPL. This feature may potentially introduce errors in the equal-latency curves that describe loudness perception at levels far above threshold. Unfortunately, equal-latency curves corresponding to far suprathreshold levels are of interest in terms of mitigating the effects of high-level noise on marine mammals (Southall et al. 2007), and they are the curves that likely deviate most from the shape of the audiogram.

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Chapter 34

Does Primary Productivity Turn Up the Volume? Exploring the Relationship Between Chlorophyll *a* and the Soundscape of Coral Reefs in the Pacific

Pollyanna I. Fisher-Pool, Marc O. Lammers, Jamison Gove, and Kevin B. Wong

Abstract Chlorophyll is the basis for ecosystem productivity in most marine environments. We report on an ongoing effort to examine whether ambient sounds are tied to chlorophyll levels. We hypothesized that an increase in food-web available energy will be distributed across trophic levels, eventually reaching sound-producing animals and increasing acoustic levels. To test our hypothesis, we compared reef environments to explore links between soundscapes and chlorophyll *a* concentrations. The study sites resided in disparate oceanographic regimes that experienced substantially different oceanographic conditions. We anticipated that the results would show differing patterns of primary productivity between sites and therefore would be reflected in the soundscapes.

Keywords Soundscape • Passive acoustics • Reef ecology • Chlorophyll *a* • Wave action • Ambient noise • Pacific • Remote islands

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1 Introduction

Coral reef environments have diverse soundscapes representative of the sound-producing marine community. Locations with suitable nutrient availability and irradiance can be characterized by their chlorophyll levels, an indicator of primary productivity. We hypothesized that an increase in food-web available energy will be distributed throughout the ecosystem's trophic levels, reaching sound-producing animals and translating into changes in the soundscape. To test our hypothesis, we compared four remote reefs with different oceanographic regimes to explore links between soundscapes and chlorophyll *a* concentrations. We chose four sites in the Pacific Ocean (Fig. 34.1) that experience limited anthropogenic pressures: Kure Atoll (28°25′ N, 178°20′ W), French Frigate Shoals (23°44′ N, 166°8′ W), Johnston Atoll (16°45′ N, 169°31′ W), and Rose Atoll (14°32′ S, 168°09′ W). These sites differ oceanographically because of seasonal and long-term differences in oceanic conditions such as sea surface temperature (SST) and wave energy (Gove et al. 2013). A passive acoustic monitoring approach was used to characterize the ambient sound on reefs (Lammers et al. 2009; Ackleh et al. 2012; Rowell et al. 2012) and satellite imagery provided information on irradiance and chlorophyll *a* (Smith 1981; Tebbs et al. 2013), which we used as a proxy for primary productivity (Platt and Herman 1983). Waves were also examined to account for periods of increased acoustic energy that may be attributed to wave noise.

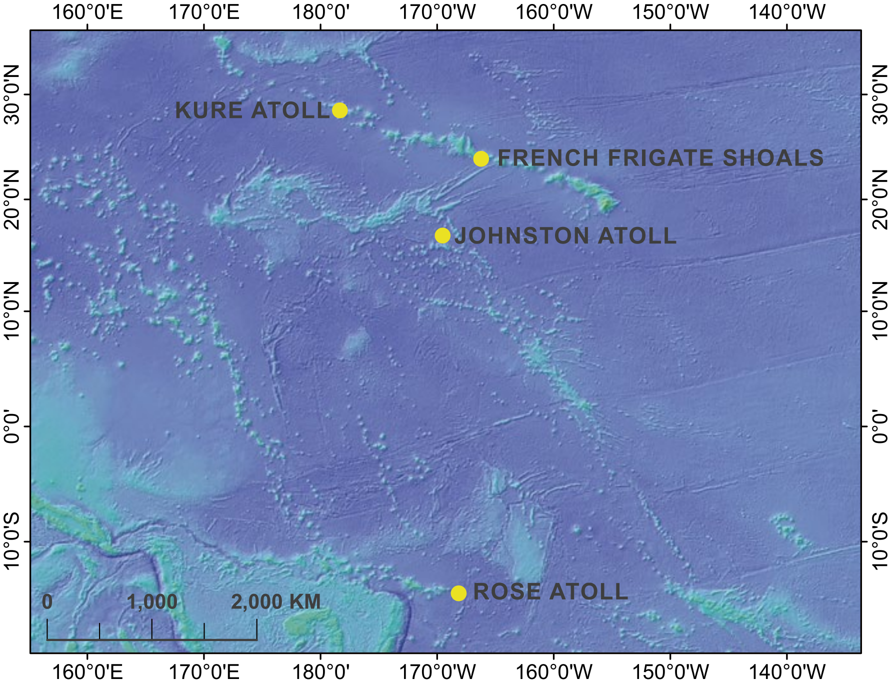

Fig. 34.1 Locations of ecological acoustic recorder (EAR) deployment sites: Kure Atoll, French Frigate shoals, Johnston Atoll, and Rose Atoll

1.1 *Site Overview*

Kure Atoll and French Frigate Shoals are part of the Northwestern Hawaiian Islands (NWHI), a group of atolls and islands at the northern end of the Hawaiian archipelago, within the North Pacific Subtropic Gyre. Kure is situated at the northern end of the archipelago while French Frigate Shoals is on the southern end of the group. On a large scale, features affecting the NWHI are the transition zone chlorophyll front (TZCF), the El Niño southern oscillation (ENSO), and the Pacific decadal oscillation.

The Johnston Atoll is part of the northern Pacific remote island area (PRIA), a geopolitical designation that includes seven islands located in the central Pacific under the jurisdiction of the United States. Oceanographically, features affecting the northern PRIAs include the north equatorial countercurrent, local upwelling, and ENSO events.

The Rose Atoll is a National Marine Monument and a National Wildlife Refuge managed by the US Fish and Wildlife Service and is considered part of the American Samoa region. Features affecting the Rose Atoll are the south equatorial current, upwelling, and ENSO events.

2 Methods

2.1 *Acoustic Data*

A network of long-term passive acoustic recorders was used to characterize ambient sounds on coral reefs as indicators of biological activity. Ecological acoustic recorders (EARs; Lammers et al. 2008) at each site captured data from varying periods between 2006 and 2010.

Weekly averages of one-octave band analyses of sound pressure levels were calculated using a custom MATLAB algorithm. The absolute value of the weekly variability in acoustic energy (ΔdB) from each octave band was used to normalize the data to identify periods of acoustic anomalies.

$$dB = \left| dB_n \quad dB_{n+1} \right|$$

Satellite-derived observations of chlorophyll *a*, irradiance, and wave action were used to develop time series datasets and quantify long-term means and periods of anomalous events

2.2 *Chlorophyll* a *and Irradiance*

Chlorophyll *a* is used as a proxy for productivity. Gove et al. (2013) produced a time series of chlorophyll *a* and irradiance products derived from moderate resolution imaging spectroradiometer (MODIS; http://modis.gsfc.nasa.gov/). A subset of these data for each site was incorporated for the time period analysis.

2.3 *Wave Energy*

A subset of data from the time series produced by Gove et al. (2013) is used to determine the time periods of increased wave action possibly linked to an increase in acoustic energy in the soundscape. The calculations use a 5-day temporal window because this period captures the episodic nature of wave events and avoids averaging out the signal of potentially heterogeneous data (Gove et al. 2013).

3 Anticipated Results

The analysis of these data is ongoing. We expect that higher phytoplanktonic biomass (measured by chlorophyll *a* concentrations) will result in more energy across the ecosystem's trophic levels. We expect these energy resources to be variable over time and that the energy flux will translate into changes in sound production patterns on the reef. The one-octave band analyses will highlight the distribution of energy across frequencies over time, providing insight on sound diversity and its variability over time. We hypothesize that there will be correlations between oceanographic variables and levels of acoustic energy in different octave bands. The effects of lunar cycles and seasonal changes in SST will also be examined to determine whether these are related to observed changes in the coral reef soundscape.

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Chapter 35
Expert Elicitation of Population-Level Effects of Disturbance

Erica Fleishman, Mark Burgman, Michael C. Runge, Robert S. Schick, and Scott Kraus

Abstract Expert elicitation is a rigorous method for synthesizing expert knowledge to inform decision making and is reliable and practical when field data are limited. We evaluated the feasibility of applying expert elicitation to estimate population-level effects of disturbance on marine mammals. Diverse experts estimated parameters related to mortality and sublethal injury of North Atlantic right whales (*Eubalaena glacialis*). We are now eliciting expert knowledge on the movement of right whales among geographic regions to parameterize a spatial model of health. Expert elicitation complements methods such as simulation models or extrapolations from other species, sometimes with greater accuracy and less uncertainty.

Keywords Conceptual models • Decision-making • Health • North Atlantic right whale (*Eubalaena glacialis*) • Parameterization

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1 Introduction to Expert Elicitation

Expert elicitation is a rigorous set of methods for synthesizing expert knowledge to inform decision making and has proven reliable and practical when field data are limited. The process of expert elicitation quantifies scientific uncertainty and minimizes inadvertent bias in the elicited information. Expert elicitation is useful for identifying plausible alternative hypotheses, estimating model parameters, and prioritizing collection of data that have considerable bearing on policy or management decisions (Martin et al. 2012). One can elicit point estimates or distributions of parameters with confidence intervals (Runge et al. 2011).

Humans typically assume that specialized knowledge makes one an expert. The expert on a particular topic has knowledge that a typical member of the general public does not, such as the approximate body length of different species of fishes or the foraging behavior of raptors. An extensive literature in psychology demonstrates that experts have predictable, manageable cognitive biases. For example, experts tend to have excessive confidence in their answers to questions. Experts also commonly have motivational bias; they believe that their judgments are based on objective facts, whereas the judgments of others are based on emotions. Experts may be unable to comprehend how others who assess the same data could arrive at a different judgment unless those individuals are unintelligent or are not acting in good faith.

Expert judgments are affected by gender and race. In the United States, for instance, Caucasian men tend to assume that the risk associated with particular human behaviors, diseases, or environmental changes is lower than do non-Caucasian men or women of any race. Confidence in judgments is affected by status. Both individuals and their peers assume that the judgment of individuals with higher status (e.g., greater number of peer-reviewed publications, seniority, years of experience) will be more accurate. However, there is no correlation between status and the accuracy of predictions. The lack of correlation reflects confusion between skill-based tasks and performance tasks. Individuals with expertise in a given task, such as a particular medical procedure, do not necessarily make accurate predictions about medical phenomena outside their specific area of expertise. Nevertheless, independent of status, some individuals tend to make more accurate predictions than others.

Judgments of the most knowledgeable individual in a group consistently are less accurate than the mean judgment of a diverse group. Accordingly, it is less reliable to seek information from one intelligent, experienced person than to apply a structured method to obtain information from many people. Use of structured methods is essential; naïve groups are likely, for example, to have unstructured discussions, to be affected by dominant individuals or group think, or to be hindered by linguistic uncertainty. Methods exist to train individuals to answer questions more effectively and to maximize the probability of accurate predictions from groups.

2 Application of Expert Elicitation to North Atlantic Right Whales

We are in the process of applying expert elicitation to develop a spatial model of the health of North Atlantic right whales (*Eubalaena glacialis*) and the environmental variables associated with health. We define health as all internal factors that affect homeostasis, such as nutritional, metabolic, and immunological status. However, before that elicitation was launched, a workshop was held in 2012 to explore the feasibility of conducting a formal expert elicitation on population-level effects of disturbance on marine mammals. To the best of our knowledge, such an elicitation had not previously been conducted for marine species. The types and strength of inferences that expert elicitation could contribute to the assessment of population-level effects of disturbance on marine mammals were unknown. We focused on the use of expert elicitation to assess whether the 2008 Right Whale Ship Strike Reduction Rule (50 CFR Part 224) has affected the probability of persistence of right whales. The elicitation was a proof of concept and was not intended to substitute for analysis of empirical data on the efficacy of vessel speed restrictions (Conn and Silber 2013).

In 2008, the National Marine Fisheries Service (NMFS) of the National Oceanic and Atmospheric Administration (NOAA) restricted the speed of vessels with lengths ≥65 ft (19.8 m) in three seasonal management areas for North Atlantic right whales (*Eubalaena glacialis*) during certain times of the year. The seasonal management areas surround critical habitats for North Atlantic right whales, which are listed as endangered under the US Endangered Species Act. The speed rule was intended to reduce the probability of death and serious injury to right whales that result from collisions with vessels. Some vessels, such as those necessary to meet national security, navigational, and human safety missions of various agencies, are exempt from the rule, but agencies still are expected to consult with the NMFS to minimize the negative effects of their operations. Because the ecological and economic effects of the rule were uncertain, the NMFS committed to assess the effects of the rule after 5 years and determine whether an extension of the rule was warranted.

Collisions of a right whale with a vessel may result in mortality, no injury, or some level of injury. Not all mortalities are observed directly, and effects of many collisions are either difficult or impossible to measure given current resources. The sound produced by vessels also may disturb right whales (Rolland et al. 2012), but the increase in stress again is difficult to measure.

We invited members of the North Atlantic Right Whale Consortium Board and other meeting attendees to participate in an elicitation in November 2012 during the consortium's annual meeting. The ~22 participants had diverse technical backgrounds (e.g., marine transportation, marine mammalogy, behavioral ecology, bioacoustics, genetics, animal welfare) and professional affiliations (e.g., universities, private companies, resource-management agencies, nongovernmental organizations). The steps we followed are transferable among expert elicitations.

3 Development of Conceptual Models

The objective of the first part of the workshop was to achieve consensus on a conceptual model of the effects of collisions on right whales. The conceptual model qualitatively represented response variables, covariates, and relationships among them. In the second part of the workshop, we elicited quantitative estimates of the principal parameters represented in the conceptual model. Here, we illustrate five of the many topics of discussion. First, the group discussed which of the three seasonal management areas included in the Ship Strike Reduction Rule (northeastern, mid-Atlantic, and southeastern) should be addressed in the conceptual model and elicitation. The group agreed to focus on the southeastern seasonal management area because it is occupied by mothers, calves, and other classes. Second, the group discussed how the elicitation might apply to making an explicit decision (albeit recognizing that because the elicitation was a brief proof-of-concept, it likely would be insufficient for policy-making). The group decided on two alternatives: no reauthorization of the rule or reauthorization of the rule as currently implemented. The group acknowledged that the decision-making process ultimately may address vessel speeds, classes, or lengths. Third, the group discussed counterfactuals, that is, whether changes in probability of collision were driven by implementation of the rule or by factors independent of the rule. For example, changes in speed might be driven by a desire to use fuel efficiently and the probability of collision might indirectly be driven by routing (Fonnesbeck et al. 2008; Vanderlaan et al. 2008). Fourth, the group discussed response variables. The group decided to focus on mean annual mortality from vessel strikes, which was assumed to be a function of probability of mortality given a collision and probability of a collision. Fifth, the group discussed injuries caused by different parts of a vessel. Bow strikes are blunt, and the probability of serious injury may decrease as vessel speed decreases. Propeller strikes are sharp and may cause injury across a range of speeds; however, suction may be greater at higher speeds.

The group achieved consensus on a conceptual model that included the most direct and indirect drivers of mean annual mortality from vessel strikes (Fig. 35.1). The group then simplified the full conceptual model to identify the parameters to be elicited (Fig. 35.2). From this simplified model, the group agreed on five estimation tasks: (1) the distribution of vessel speeds, expressed as a probability density function, given status quo implementation of the speed rule; (2) the distribution of vessel speeds, expressed as a probability density function, given expiration of the speed rule; (3) the probability of collision given status quo implementation of the speed rule; (4) the probability of collision given expiration of the speed rule; and (5) the probability of lethal injury conditional on collision as a function of vessel speed. As a first approximation, the group assumed that the probabilities for multiple species of large whales estimated by Vanderlaan and Taggart (2007) were applicable to this elicitation process.

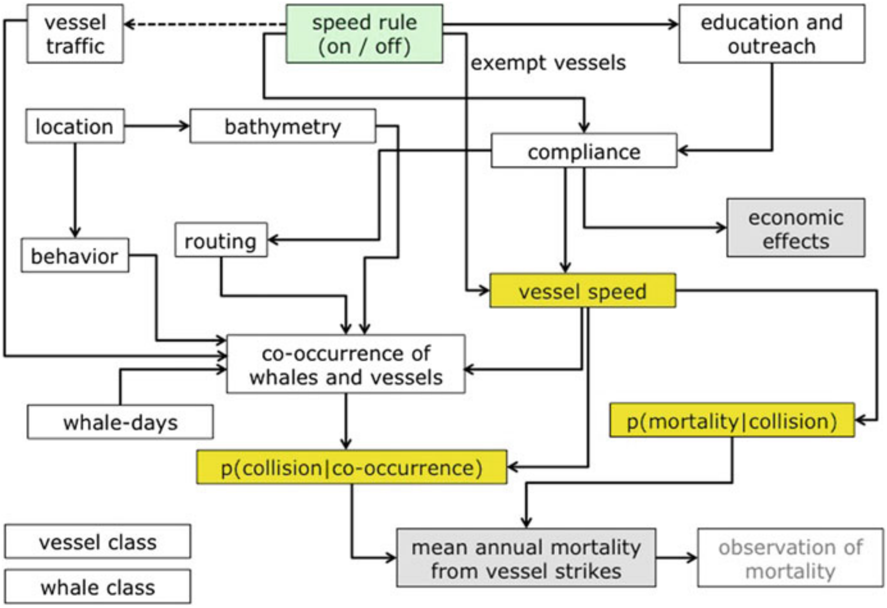
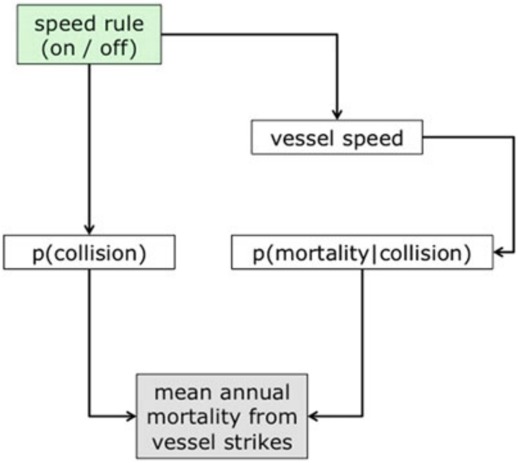


Fig. 35.1 Conceptual model of mean annual mortality of North Atlantic right whales from collisions with vessels ≥65 ft in the southeastern seasonal management area. Vessel class and whale class were recognized as potential drivers of mortality but were not included in the conceptual model

Fig. 35.2 Simplified conceptual model of mean annual mortality of North Atlantic right whales from collisions with vessels ≥65 ft in the southeastern seasonal management area



4 Elicitation of Parameter Estimates

Each participant was given a questionnaire with the following four questions. First, in the southeastern US seasonal management area, given speed regulation, what will be the average speed of vessels longer than 65 ft in areas in which they may intersect whales? Second, in the southeastern US seasonal management area, without speed regulation, what will be the average speed of vessels longer than 65 ft in areas in which they may intersect whales? Third, in the southeastern US seasonal management area, given a population of 200 right whales and given speed regulation, how many impacts would you expect in 5 years from vessels over 65 ft? Fourth, in the southeastern US seasonal management area, given a population of 200 right whales, without speed regulation, how many impacts would you expect in 5 years from vessels over 65 ft?

Each question required four responses (i.e., estimates of four quantities), framed as follows. First, realistically, what is the lowest value it could be? Second, realistically, what is the highest value it could be? Third, what is your best estimate (the most likely value)? Fourth, how confident are you that the interval you provided contains the truth (in percent)?

Group discussion conditioned each question before individuals provided their four responses to it. For example, the average speed (questions 1 and 2) was the average instantaneous speed of multiple vehicles, with replacement. The set of vessels included those exempted from the rule. Routing was assumed to be the status quo, irrespective of whether the rule was implemented, and North Atlantic right whales were assumed to be active in the southeastern seasonal management area.

For questions 3 and 4, the number of collisions (impacts) included those that caused mortality, an injury of any severity, or no injury. All whales were assumed to be in the southeastern seasonal management area at the same time. The number of impacts over the 5-year period was the sum of expected impacts in each year.

Following the conditioning, the questions were addressed one at a time. First, individuals wrote their responses on the paper questionnaires. Second, given the time constraints for the workshop, individuals called out their responses while one person plotted values on a whiteboard. In a more formal elicitation, facilitators would have gathered anonymous responses. Third, the group discussed the responses to each question. For instance, individuals explained why they believed certain low or high values were accurate. Fourth, after discussion, individuals again provided responses. The full set of responses was compiled after the workshop by the facilitators.

Following the second step, we entered the means and variances of group responses into models of vessel-speed distributions and probability of collision. Therefore, before the workshop adjourned, the group was able to visualize how expert elicitation could be applied to parameterize models and obtain inferences that might inform decision making.

5 Results

First, the expert panel predicted that the speeds of individual vessels in the southeastern US seasonal management area are normally distributed with a standard deviation of 3 knots (80% CI; 2–4 knots). Assuming the latter, the experts' predicted distribution of realized vessel speeds was 11.3 knots (80% CI; 6.2–16.5 knots) with the speed rule in effect and 17.6 knots (80% CI; 11.2–24.0 knots) without the speed rule in effect.

The expert panel predicted that in the southeastern US seasonal management area from 15 November to 15 April (the period of time during which speed restrictions are in effect), the probability of collision between a vessel and a right whale would be 0.006 (80% CI; 0.002–0.011) with the speed rule in effect and 0.015 (80% CI; 0.008–0.024) without the speed rule in effect.

To calculate the annual mortality rate, we first integrated the probability of lethal injury conditional on collision over the estimated distribution of vessel speeds. That is, we accounted for the statistical distributions of both vessel speeds and collision probability. We then multiplied the probability of lethal injury by the probability of collision. The resulting distribution suggested that the annual probability of mortality would be 0.0027 (80% CI; 0.0003–0.004) with the speed rule in effect and 0.0120 (80% CI; 0.0042–0.0204) without the speed rule in effect. The distribution of these quantities is meant to fully capture the uncertainty in the composite parameters expressed by the experts.

These results are not directly comparable to those of Conn and Silber (2013), who focused on the relationship between vessel speed and the probability of lethal injury and the change in probability of mortality associated with speed reductions. In this case, however, it would be possible to examine the two sets of results and potentially explore the difference in detailed empirical and expert-based estimates.

6 Potential Practical Applications

The workshop illustrated the feasibility of conducting a formal expert elicitation on population-level effects of disturbance on marine mammals. We demonstrated that after a short training session, a diverse group of experts could estimate parameters that are directly relevant to rigorous scientific analyses. Given that expert elicitation has a strong conceptual basis and results from elicitations in various disciplines have been independently verified, the method contributes to generation of the best science available for decision making.

Processes analogous to those described here might further elucidate population-level effects of the Speed Rule on North Atlantic right whales. For example, we might elicit relations between vessel behavior and various levels of injury or elicit other parameters in Fig. 35.1. Because there are few data on the movements of individual whales, we have begun to use expert elicitation to parameterize a model of movement among the nine geographic regions that collectively represent the majority of the species' habitat. We then will estimate population-level movement in monthly time steps and validate the model by comparing the latter estimates to data from satellite telemetry.

Management of many rare and endangered species is hindered by a lack of data on population dynamics and responses of the species to particular disturbances. Researchers have explored multiple methods to fill the data gaps when species are not only rare but detection probabilities are low. For example, simulation models or extrapolations from better known species sometimes have been applied to estimate population-level effects of disturbance. Expert elicitation complements such methods and in some cases may achieve greater accuracy and lower uncertainty.

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Chapter 36
Current Status of Development of Methods to Assess Effects of Cumulative or Aggregated Underwater Sounds on Marine Mammals

Erica Fleishman, Bill Streever, Robyn Angliss, Christopher W. Clark, William T. Ellison, Adam Frankel, Jason Gedamke, Matthias Leu, Megan McKenna, Roberto Racca, Samantha Simmons, and Robert Suydam

Abstract There are no standards for assessment of the cumulative effects of underwater sound. Quantitative assessments typically consider a single source, whereas qualitative assessments may include multiple sources but rarely identify response variables. As a step toward understanding the cumulative effects of underwater sound, we assessed the aggregated sounds of multiple sources received by migrating bowhead whales (*Balaena mysticetus*). The quantitative method models the sound field from multiple sources and simulates movement of a population through it. The qualitative method uses experts to assess the responses of individuals and populations to sound sources and identify the potential mechanisms. These methods increase the transparency of assessments.

Keywords Aggregate effects • Behavior • National Environmental Policy Act • Population dynamics • Stressor

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1 Standards for Effects Assessment

Environmental legislation or guidance in the United States typically directs federal agencies to use the "best" science or scientific methods in making their decisions. For example, the Endangered Species Act refers to use of "the best scientific and commercial data available," "the best appropriate data," and "the best available biological information." Guidance from the US Council on Environmental Quality (CEQ) on implementation of the National Environmental Policy Act, which requires proposals for federal actions to detail substantial effects on "the quality of the human environment" that may be associated with the action, requires decisions to "be supported by the best analysis based on the best data we have or are able to collect" and notes, "Cumulative effects analysis needs to apply the best science and forecasting techniques" (CEQ 1997).

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Although there is no consensus on the meaning of "best," the Administrative Procedure Act and Information Quality Act elucidate what the courts might expect of federal agencies (Murphy and Weiland 2011). Best generally encompasses scientific quality, objectivity, evidence-based inference, and practical value (Murphy and Weiland 2011). Additionally, scientific integrity usually demands explicit, measurable objectives; reliable data with metadata; rigorous, repeatable analyses; quantification of uncertainty and effect sizes; inferences based strictly on data and results; and clear differentiation of opinion from facts.

The requirements of some states also set a high standard for agencies' application of scientific information to decision making. For example, California's Environmental Quality Act (CEQA) requires that agency determinations be supported by "substantial evidence," "enough relevant evidence and reasonable inferences from this information that a fair argument can be made to support a conclusion, even though other conclusions might also be reached" (Title 14 California Code of Regulations §15,384). Additionally, CEQA requires environmental impact reports (EIRs) to serve as informational documents.

In practice, legislative mandates on effects assessments can be difficult to implement rigorously, especially when the aim is to evaluate potential responses of diverse species to many human activities over large areas or time periods. Even when biological information is ample, projections of the effects are complicated by a variation in responses to human activities and to stressors created by those activities, among, for example, species, sexes, life stages, and behaviors (e.g., breeding, foraging, migrating). Furthermore, physiological or behavioral responses may have negligible, sublethal, or lethal effects, and individual-level effects may not propagate to the population. Here, we define stressors as entities or processes that have negative effects on individuals or populations (e.g., reduce probabilities of survival, reproduction, or persistence) within a given location and time period. Thus, stressors do not exist independent of context but are defined relative to response variables.

2 Common Estimates of Cumulative Effects

We use cumulative to refer to the net effects of all human activities on a response variable over a given period of time. We use aggregate to refer to the net effects of concurrent human activities. Evaluations of the effects of multiple actions that create one type of stressor are relatively common. Examples include assessment of effects of multiple anthropogenic sounds on marine mammals or effects of multiple parasites, viruses, or pesticides on bumble bees (*Bombus* spp.) or honey bees (*Apis mellifera*; Meeus et al. 2011).

Rigorous assessment of the effects of multiple stressors is increasingly facilitated by advances in technology and reductions in the cost of satellite remote sensing, geographic information systems, and computational speed and power. For example, researchers have characterized the locations and potential ecological effects of human presence and activities, the human footprint (Sanderson et al. 2002), at global (Sanderson et al. 2002), national (Theobald et al. 2012), and regional (Leu et al. 2008) levels. The footprints are contemporary, but some of the activities that created the footprint may have been historical. In most cases, the footprints do not account for seasonal or shorter term changes in the extent or magnitude of human presence and activities. First, in most cases, the physical effect area, the actual area occupied by anthropogenic features, is delineated. Then the ecological effect area, which is the zone affected indirectly by those features, can be estimated. The intensity of effects can be estimated with respect to either species or measures of ecological status. For instance, gradients of permeability allow the estimation of the effects of human activities or features, such as agriculture, housing density, presence of roads, and highway traffic, on the connectivity of large natural landscapes (Theobald et al. 2012).

3 Challenges to Effects Analysis

Definitions, assumptions, and methods of cumulative effects assessments in environmental impact statements (EISs) and EIRs often do not dovetail with the best scientific practice. Assessments often are simply a list of past, present, and foreseeable human actions that may be stressors. This hinders the rigorous estimation of effects and leaves the assessments vulnerable to legal challenges. Guidelines for the CEQA (Title 14 California Code of Regulations §15,000 et seq.) specify, "An EIR should be prepared with a sufficient degree of analysis to provide decision makers with information which enables them to make a decision which intelligently takes account of environmental consequences . . . The courts have looked not for perfection but for adequacy, completeness, and a good faith effort at full disclosure." For example, assumptions about species occurrence in many EISs and EIRs are based on reviews of the literature or existing data without regard to criteria such as temporal extent of the data (e.g., presence may be assumed even if the species was observed many years earlier); whether field surveys used standard methods, were replicated, and were conducted during the period when a given species was most likely to be present; and whether sampling was equal per unit area. Probabilities of detection rarely are estimated. The courts have commented that observations are not studies and reports of observations are not analyses (SCLA 2012).

Additionally, EISs and EIRs often do not quantify criteria for significant effects. A recent terrestrial EIS/EIR referenced substantial effects on certain species, substantial interference with movement, substantial reduction in habitat, and substantial reduction in a species' range, all without definition (USACOE and CDFG 2010). Similarly, levels of effect also may not be defined. The same EIS/EIR referred to four levels of effect: (1) significant, (2) adverse but not significant (i.e., a measurable but not significant effect), (3) less than significant, and (4) not significant because no effect would occur (USACOE and CDFG 2010). Moreover, direct, indirect, and secondary effects were differentiated on the basis of geography relative to a development project rather than on the basis of stressors or response variables.

Professional judgments and scientific assessments in some EISs and EIRs may be accurate but are not documented in a manner that could readily be replicated. For example, recent US Navy EISs for training and testing activities for Hawaii and Southern California and for the Atlantic Fleet referenced “Internet searches” and evaluation of “Web sites” for “credibility of the source, quality of the information, and relevance of the content” of information for assessments of cumulative effects but without details of search engines, URLs, or criteria for credibility, quality, or relevance. Final determinations of whether the effects were biologically significant appeared to have been qualitative and were not explained in sufficient detail to meet the “informational document” criterion of legislation such as CEQA. These limitations have practical relevance given that the courts have held it is unacceptable to say “our expert provided this analysis and his ‘expert opinion’ constitutes substantial evidence” (SCLA 2012).

4 Quantitative Assessment of Aggregated Effects

We aimed to develop transparent, scientifically rigorous methods to assess the aggregated effects of anthropogenic underwater sound on marine mammals. First, we developed a quantitative method for estimating exposure and potential responses of marine mammals to multiple sources of continuous and impulsive sound. The method, described by Streever et al. (2012), has eight steps and is transferable among sound sources, ecosystems, and species or populations. In steps one through four, boundaries on the assessment are set and response variables and covariates are identified. First, identify the target of assessment, whether a species, population, or class (e.g., sex or age class). Second, identify the spatial and temporal bounds of the assessment, which should be biologically meaningful. Third, identify continuous and impulsive sources of sound occurring within the assessment boundaries. These sources may occur in different locations and may vary during the assessment period. Fourth, estimate which of these sources are likely to create stressors to the target. For example, permanent threshold shift (irreversible loss of hearing) may result from high levels of exposure to seismic air gun arrays used to explore for oil and gas. In steps five through eight, sound fields and then exposure and responses of the target animals are modeled. Fifth, model and aggregate sound fields generated by individual sources during a defined period of time. Sixth, simulate movements of animals through the aggregated sound fields. Seventh, estimate the cumulative sound exposure levels for each modeled animal over the assessment period. Eighth, sum the dosimetric exposure measure for each modeled animal to estimate both the population-level exposure to each sound source and the aggregated exposure to all sources.

As a proof of concept to develop and validate the method, we conducted a case study on bowhead whales (*Balaena mysticetus*). This species is listed as endangered under the US Endangered Species Act, as depleted under the US Marine Mammal Protection Act, and as an Appendix I species, the highest level of protection, under the Convention on International Trade in Endangered Species of Wild Fauna and

Flora (CITES). Additionally, native communities in Arctic Alaska meet cultural and nutritional needs through an annual subsistence harvest of a small proportion of the population. We bounded our assessment in space to the Alaskan Beaufort Sea (about 144–152°W) and in time from 1 September through 23 October. These extents encompass most of the population's westward migration from feeding grounds in the Canadian Beaufort Sea through the Alaskan Beaufort Sea and into the Chukchi Sea. We modeled sources of anthropogenic sound for the 2008 season, a period in which multiple seismic sources were operating. We identified sources of sound related to oil and gas production, seismic exploration, and vessel traffic (Funk et al. 2010; NOAA 2013). Our intent was not to re-create precisely the sound field during autumn 2008 but to develop a realistic, transferable model of sound sources and exposures. We modeled the sound fields generated by the Northstar and Oooguruk production islands, one offshore and one nearshore tug barge, and two offshore and three nearshore seismic survey operations. The offshore seismic operations deployed an ~3,000 in.^{3} air gun array at two sites, whereas at various times during the assessment period, the nearshore operations simultaneously deployed two air gun arrays of either ~900 in.^{3} or ~450 in.^{3}. Although seismic operations are mobile, we maximized model tractability by assuming that sound sources were stationary.

We estimated three acoustic metrics: per-pulse or per-second sound exposure level (SEL; in dB re 1 μPa^2·s), instantaneous root-mean-square (rms) sound pressure level (SPL; in dB re 1 μPa), and cumulative sound exposure level (CSEL; in dB re 1 μPa^2·s), i.e., aggregated exposure to all sound sources over time (Madsen et al. 2006). We used existing models (e.g., Hannay and Racca 2005; MacGillivray 2006) to estimate source levels for air gun arrays and sound fields produced by individual sources. We used publicly available bathymetry data and published models (e.g., Hamilton 1980; Teague et al. 1990) to derive sound-velocity profiles and geological parameters that affect acoustics in the Alaskan Beaufort Sea.

We used the individual-based Acoustic Integration Model (AIM; Frankel et al. 2002) to simulate the movement of bowhead whales through the sound field and to estimate their exposure over time. The parameters in this model, values of which we derived from published empirical data, expert scientific knowledge, and traditional ecological knowledge, were bowhead whale population size, percentage of the population in the Alaskan Beaufort Sea throughout the migration period, distance of individuals from the coastline, direction and speed of motion, dive time and depth, surface time, maximum depth and offshore distance, SEL, and aversion to sound. The model measured values of the location and exposure parameters at 30-s intervals throughout the simulation. We ran simulations both with and without aversion. We modeled aversion as a function of the SPL at which an animal would respond, probability of response, aversion angle, and frequency at which the animal evaluates the sound field.

We found that maximum received SEL at different water depths changed over time as the composition and scheduling of human activities changed. Different sources dominated the sound field over time at any given location. Instantaneous and cumulative exposure depended on whether animals swam relatively near or far from the shoreline and whether they averted from certain SPLs. The population-level CSEL was considerably lower when the animals were assumed to have an a priori probability of averting from SPLs ≥160 dB than when no aversion was assumed. However, mean travel distances (and, by extension, energetic costs) did not differ substantially as a function of aversion, likely because the modeled variability in heading had a more substantial effect on travel distance than responses to high sound levels. In some field studies, bowhead whales responded to received SPLs <160 dB (see Richardson et al. 1995), but for modeling tractability, we assumed bowhead whales did not have a behavioral response to received levels of sound <160 dB.

5 Qualitative Assessment of Aggregated Effects

In parallel with the quantitative methods, we are developing a qualitative method for estimating aggregated effects of anthropogenic sound on marine mammals that might be applied when empirical data are insufficient to parameterize a quantitative model. The method is also designed to organize and render transparent any assumptions about relationships between species and human activities, sources of information, and levels of certainty. Thus, it would be possible to trace fully the basis for the regulatory determinations of whether the effects are significant.

The first four steps in the quantitative method, which set assessment boundaries and identify primary sound sources, are also implemented in the qualitative method. The qualitative method places greater emphasis than the quantitative method on documenting major uncertainties about the responses of a given species to particular activities or stressors. It also requires, between steps two and three, specification of alternative, a priori criteria for significant effects. Accordingly, there will be an explicit basis for determining whether marine mammals have been harassed or harmed by one or more activities. Although the criteria per se may be debated, we anticipate that the foundation of evidence for decisions will increase.

The qualitative method relies on rigorous methods for expert elicitation to identify mechanisms by which each stressor may affect response variables such as survival, reproduction, or population viability. Response variables are likely to vary among assessments. In the bowhead whale example above, for instance, no stressor was expected to cause mortality. Expert elicitation is a rigorous set of methods for synthesizing expert knowledge to inform decision making and has proven reliable and practical when field data are limited. The process of expert elicitation quantifies scientific uncertainty and minimizes inadvertent bias in the elicited information. Expert elicitation is useful for identifying plausible alternative hypotheses, estimating model parameters, and prioritizing collection of data that have considerable bearing on policy or management decisions (Martin et al. 2012). One can elicit point estimates or distributions of parameters with confidence intervals (Runge et al. 2011).

In this method, expert elicitation is also used to estimate, for each stressor, the probability of a change in the response variable, the magnitude of that change, and the expert's confidence in the latter two estimates. Each expert is required to document fully the data, ancillary knowledge, and assumptions that informed their estimates. The method allows the estimation of the aggregated effects of all stressors and of individual stressors on individuals or populations.

6 Ongoing Work

Further work is needed to improve our quantitative and qualitative methods of assessing cumulative and aggregated effects of underwater sound sources. From its outset, the work described here was intended to inspire complementary efforts. The quantitative method could be applied, whether in its current state or with enhancements, to assess the effects of major human activities. However, the technical challenges of acoustic and simulation modeling likely will limit its use to activities that are controversial, of political interest, and well funded. We anticipate that the qualitative method, although not yet finalized to a point at which it can be used to assess effects, eventually will prove more routinely applicable.

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Chapter 37

Seismic Survey Footprints in Irish Waters: A Starting Point for Effective Mitigation

Thomas Folegot, Dominique Clorennec, Gerald Sutton, and Mark Jessopp

Abstract The noise footprint of a given activity is defined as the area where the noise from the activity spreads into the ocean at levels above the existing statistical ambient noise. The noise footprints of seismic surveys in Irish waters from 2,000 to 2,011 have been estimated using Quonops, a global ocean noise prediction service. Noise footprints are converted into sound exposure levels to evaluate the cumulative risks toward high-, mid-, and low-frequency marine mammals. The results demonstrate large variability in risk areas as a function of existing ambient-noise levels, season, survey location, and characteristics of the survey.

Keywords Marine Strategy Framework Directive • Noise • Quonops • Marine mammals • Monitoring

1 Introduction

Anthropogenic noise is considered an acoustic pollutant, with an anticipated increase through the expansion of shipping, resource extraction, and offshore development. Marine mammals rely on sound for navigation, feeding, and communication and are known to be particularly sensitive to anthropogenic noise. Over the last 10 years, a significant amount of data on the effects of sound on marine mammals has been produced, with impacts ranging from death due to physical injury and auditory damage to behavioral and habitat use changes (Hastings and Popper 2005; Southall et al. 2007). The effects depend on various factors, including an overlap in

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space and time with the organism and sound source; duration, nature and frequency content of the sound; received level; and context of exposure (e.g., animals may be more sensitive to sound during critical times such as breeding or nursing; Tasker et al. 2010). In areas of high levels of anthropogenic noise, listening horizons may also be significantly reduced (National Research Council 2005; Clark et al. 2009). This has stimulated much debate regarding how to address the potential impacts of underwater noise on marine mammals and develop mitigation measures.

The Marine Strategy Framework Directive (MSFD) aims at achieving or maintaining good environmental status (GES) by 2020 with Descriptor 11 (Noise), taken to mean “anthropogenic sound that has the potential to cause negative impacts on the marine environment.” Seismic surveys represent potentially large anthropogenic contributions to soundscapes and may prevent attainment of GES. This study combines expertise in sound propagation modeling and marine biology to develop potential risk maps for marine mammals in Irish waters. The outputs of noise propagation modeling will be used to inform design of a basin-scale assessment program that will lead to focused mitigation strategies.

2 Methods

We used the proprietary Quonops ocean noise monitoring and prediction system (Folegot 2010) to model soundscapes in Irish waters. The model domain ran from 3° to 25° W longitude and 46° to 59° N latitude, utilizing a 0.5° × 0.5° grid over the shelf and nearshore waters and 1° × 1° grid in offshore waters. Quonops uses a Monté Carlo approach to determine the seasonal statistics of the sound fields and describe the spatiotemporal distribution of noise levels generated by human activities across the Irish exclusive economic zone (EEZ) in terms of probability. The noise-level distribution in the water column and sediments depends largely on the noise sources present, bathymetry, and environmental conditions including temperature, salinity, sea state, and sediment type. Therefore, these variables are included in the Quonops modeling framework. Bathymetry data come from the freely available GEneral Bathymetric Chart of the Oceans (GEBCO) database. Seabed sediment distribution data were sourced from the MeshAtlantic project (www.meshatlantic.eu) and matched with Applied Physics Laboratory (1994) equivalents for which specific sound absorption figures were available based on expert knowledge. Sediment data were lacking for a proportion of cells, and these were allocated a nominal “sand” classification on the grounds that this sediment type dominated the offshore sediment types in the area for which data were available. Modeled data for temperature/salinity profiles were obtained from the Irish Marine Institute using the northeast Atlantic oceanographic forecast model, which provides temperature/salinity profiles at a 2-km grid resolution. Seasonal wave heights across the model domain were computed from the hindcast of dynamic processes of the ocean and coastal areas of Europe (HIPOCAS) data (Vijaykumar et al. 2003), with the mean value for each season used in unpopulated grid cells.

To represent the spatial and temporal distribution of shipping traffic for noise-modeling purposes, automatic identification system (AIS) data were obtained from the Department of Transport, Tourism and Sport and processed to give ship density per square kilometer for each season. For ships, sound sources were modeled as point sources near the surface. Data for modeling propagation of impulsive anthropogenic sound produced by air guns, typically used for seismic surveying, were taken from records maintained by the Petroleum Affairs Division of the Department of Communications, Energy and Natural Resources between 2001 and 2011. The repetition rate for the air gun firing was inferred as 20 s because actual values were not reported due to commercial sensitivity. Seismic air gun sound sources were modeled as point sources at the actual depth provided by the operators.

The statistical definition of ambient noise (contributions from environmentally generated noise such as waves and currents plus shipping noise) was used to derive the noise footprint of seismic surveys. This is defined as the area where the noise produced by one pulse is above the median (50th percentile) of existing noise not related to seismic activity. A high-resolution autonomous underwater sound-recording device was deployed for 16 days outside Cork Harbour on the south coast of Ireland to accurately characterize the local sound field and ground truth the predictive sound maps produced by the model.

The perceived noise footprint of marine mammals is based on the hearing sensitivity in functional groups of “high-,”, “mid-,” and “low-” frequency cetaceans and “pinnipeds” based on Southall et al. (2007). Because all the sound fields have been based on a frequency band of a one-third octave of 125 Hz, noise levels have been adjusted upward by a factor of 11 dB, which captured the energy that might be in the other frequency bands (i.e., between 63 Hz and 63 kHz). The risk to marine mammals posed by seismic noise fields is based on thresholds for the risk of permanent hearing threshold shift (PTS), risk of temporary hearing threshold shift (TTS), and behavioral responses taken from the literature (Southall et al. 2007; Lucke et al. 2009). Risk assessment is based on four depth ranges based on the diving capabilities and depth preferences of marine mammal species (Watwood and Buonontony 2012). Because thresholds for behavioral changes are not yet established for mid- and high-frequency species, a gradient proportional to the perceived noise level is used to indicate potential behavioral changes.

3 Results

A minor divergence between the cumulative frequency curves from modeled and field deployments occurred toward the lower end of the power spectrum (representing environmental contribution) and was attributed to the fact that the modeling was undertaken using a fixed sea state. In the upper part of the power spectrum (anthropogenic contribution), the match was much closer. The standard calibration procedure for modeling iteratively applies small offsets to environmental variables (degrees of freedom) to obtain a close match with field observations. In this case, the match was accepted at first pass and the iterative matching procedure was not required.

Ship traffic noise spreads over very large areas, well beyond the standard navigation routes, and is added to the background noise against which seismic surveying activities are detected. However, the results suggest that Irish waters are relatively quiet compared with areas that are close to shipping routes.

The distribution of seismic activity over the 11 years (2000–2011) showed a clear aggregation of activity coinciding with the major hydrocarbon basins. For a single survey conducted from 10 June to 22 July 2010 in the Porcupine Basin with a 6,180 in.[3] air gun, the estimated total number of bangs during the survey was 181,440, by extrapolation (and in the absence of actual data on air gun activity during the survey), with the location of air gun activity within the survey based on the spatial resolution of the data reported to the Department of the Environment, Community and Local Government (DECLG). This same rationale was reproduced for each survey, providing a total of 35 individual seismic scenarios.

A large variability in seismic footprints was noted due to location. Surveys covering a large area also had a greater variability due to variability in survey location, bathymetry, and bottom sediment. Figure 37.1a–c shows the cumulative energy arising from the total number of air gun pulses within each survey as it moved across the survey area for three representative surveys (survey no. 6, survey no. 23, and survey no. 34, respectively). The footprints are conspicuously asymmetrical (rather than a simple sphere), which arises from the environmental context of the survey (in terms of the spatial variability of the bathymetric terrain and the movement of the source through that terrain).

Figure 37.2 shows the cumulative risk map scenario for the full duration of survey no. 22 for low- and high-frequency cetaceans (assuming no movement) based on thresholds for TTS, PTS, and behavioral responses. The size of the area that may entail a significant impact is very much more extensive and irregular than may be inferred from the typical bang days reporting format and may result in areas of impact that completely encompass the preferred habitat or range of some marine mammal species.

4 Discussion

Underwater sound propagates very rapidly (~1,500 m/s) over large distances (thousands of kilometers). Sound propagation in the ocean is largely dependent on the topography of the ocean floor and the nature of the sediments (Guiesse and Sabathié 1964). The modeled area is bathymetrically complex, with strong contrasts between the relatively flat coastal shelf area and large offshore features such as the Rockall Trough, Porcupine Seabight, and Hatton Bank, all of which exert a significant influence on the resulting propagation patterns.

Although consistent with the scientific and technical state-of-the-art, the results are of a predictive nature and have only been calibrated against ocean acoustic field surveys in one part of the model domain (Cork Harbour). Although there was excellent agreement between the modeled outputs and validation data, uncertainty in the

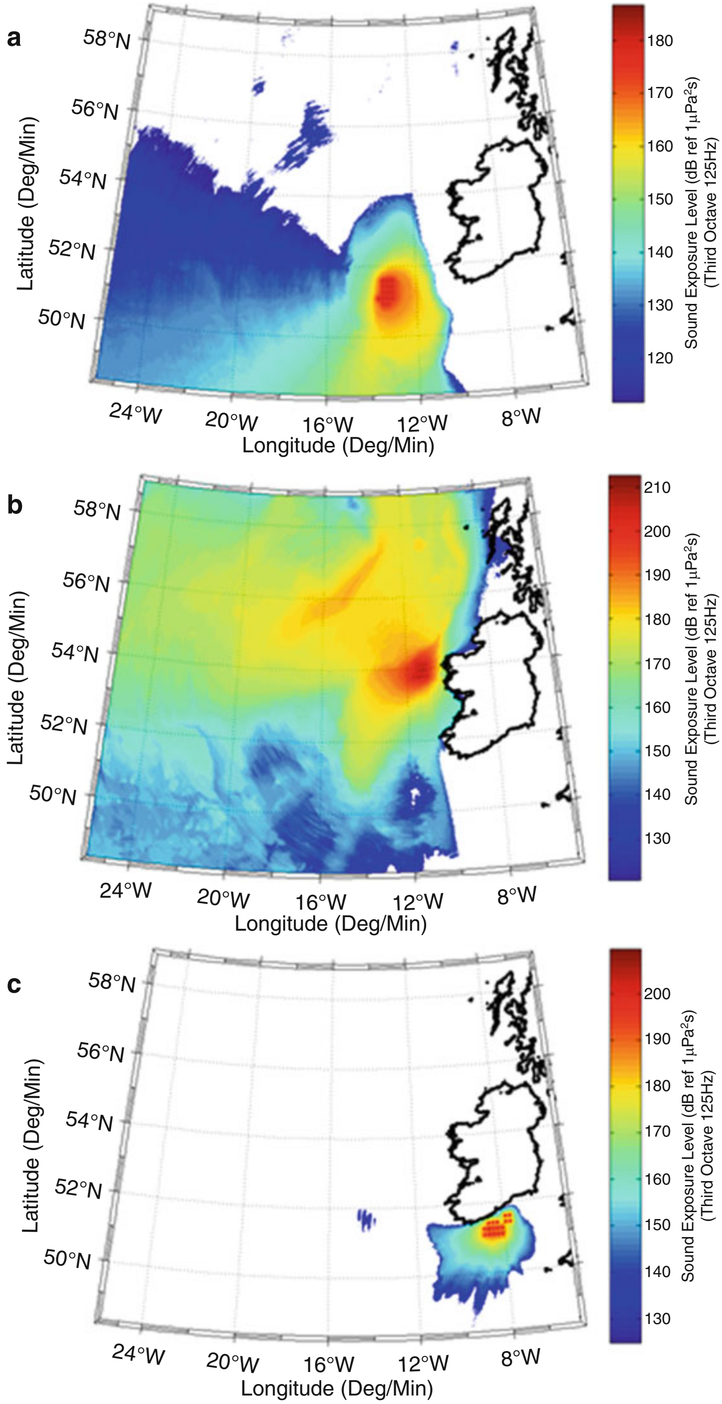

Fig. 37.1 Cumulative energy of a single air gun footprint for survey no. 6 in summer 2000 (**a**), survey no. 23 in autumn 2000 (**b**), and survey no. 34 in spring 2011 (**c**)

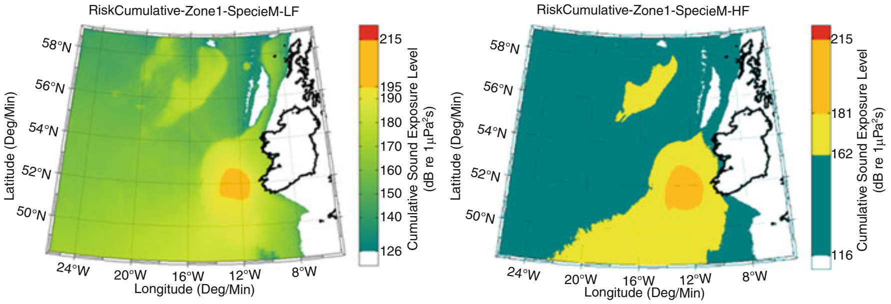

Fig. 37.2 Cumulative risk at the end of the full duration of survey no. 22 (181,441 seismic air gun "bangs") between 0 and 100 m depth for low-frequency (*left*) and high-frequency (*right*) cetacean species. *Orange* is area of temporary hearing threshold shift, *yellow* is area of behavioral response, and *green* is area of no predicted impact on marine mammal species

model parameters is taken into account by the Monté Carlo approach. This enables the parameters to be varied within a range of uncertainty. Although our approach also provides a reasonable description of shipping activities, it should not be regarded as a fully comprehensive description of all vessel traffic. The coastal AIS network cannot capture signals from vessels that are far from shore, resulting in offshore vessel movements being underrepresented and the contribution from fishing vessels is likely to be underrepresented because a (unknown) proportion may not operate the AIS. However, model outputs represent a viable and feasible assessment of the propagation of underwater noise and the potential impact on marine mammal species.

In general, footprints from seismic surveys tend to be much larger in deep water where the ambient-sound field is relatively quiet. Much of the seismic activity was associated with the major hydrocarbon basins, concentrated along the deep waters of the west coast of Ireland. As a result, large cumulative footprints for seismic activities were noted. The resulting seismic footprints were converted into risk maps for marine mammal functional groups based on their hearing sensitivity and depth preferences. Given how difficult it is to study living animals in the wild, most of the knowledge on the hearing sensitivity of marine mammals and the impact of sound on their hearing has been acquired through the study of captive individuals. To date, the audiograms of 32 species of marine mammals have been measured (Simard and Leblanc 2010), and further work will be required to determine the hearing sensitivity and thresholds for the remaining species occurring in Irish waters.

At the individual level, noise impacts can range from changes in the ability to communicate, hunt, or reproduce to the complete or partial physiological destruction of hearing capacity, which can lead to death in the most extreme cases. At the population level, noise impacts can range from a decrease in birth rate and an increase in infant mortality to site abandonment. This study addressed the level of impact on the individual in terms of permanent hearing impairment, temporary hearing impairment, and behavioral disturbance based on hearing sensitivity. A large variability in the area of potential impact was noted. The potential risks to marine mammals posed by the sound fields associated with single shots were localized to the source itself. However, cumulative sound fields arising from multiple shots either within a survey or from multiple concurrent surveys generate very large areas of potential risk. The footprint for TTS and, in particular, the area where behavioral responses are expected can be very large for some surveys and may well encompass large areas of the species range. However, during the first 3 h (540 seismic bangs) of a survey, an animal might travel a few kilometers away from the noise source, which should reduce exposure to sound. If perceived noise masks biological cues used for foraging or communication or if behavioral responses result in the disruption of breeding or foraging activities, then surveys conducted over longer temporal scales (average survey duration over the 11 years was 25 days) may have serious consequences at the population level.

In the context of monitoring and reporting under the MSFD, the EU Technical Subcommittee on Marine Noise (TSG Noise) identified two key issues for the reporting of bang days or the number of days in a year in which an impulsive sound (such as seismic sonar) has been transmitted. The first concerned the dimensions of the grid that should be used, which is based on a rule of thumb largely influenced by the practical requirements of northeastern European countries that have predominantly shallow EEZ territories with a uniform terrain. However, Ireland and the United Kingdom have a much more variable underwater terrain that has important consequences in terms of sound propagation. Second, the cumulative effect of impulsive noise is likely to entail a significant impact on marine animals (Southall et al. 2007) and is not addressed in the current bang days concept.

Given the relative size and extent of Ireland's marine territories in comparison to population and gross national product (GNP), the effective monitoring and environmental status reporting for anthropogenic noise throughout the full extent of the EEZ (9× land area) could be a costly and onerous responsibility, particularly if based solely on field measurements. The output of this research currently represents the only realistically cost-effective and statistically verifiable alternative to broad-scale direct monitoring. Hence, we recommend a combined approach based on an appropriate modeling framework in combination with strategic device deployments as a source of calibration and verification of model outputs.

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Chapter 38
Stochastic Modeling of Behavioral Response to Anthropogenic Sounds

Adam S. Frankel, William T. Ellison, Kathleen J. Vigness-Raposa, Jennifer L. Giard, and Brandon L. Southall

Abstract The effect of anthropogenic sounds on marine wildlife is typically assessed by convolving the spatial, temporal, and spectral properties of a modeled sound field with a representation of animal distribution within the field. Both components benefit from stochastic modeling techniques based on field observations. Recent studies have also highlighted the effect of context on the probability and severity of the animal behavioral response to sound. This paper extends the stochastic approach to three modeling scenarios, including key contextual variables in aversion from a given level of sound and as a means of evaluating the effectiveness of passive acoustic monitoring.

Keywords Noise • Behavioral response • Context • Acoustics • Propagation • Stochastic modeling • Animat

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1 Introduction

Assessing the impact of anthropogenic sounds on marine wildlife is typically accomplished through a combination of acoustic modeling of the source sound field integrated with either an average distribution or a simulated movement of individual animals (animats) through the sound field. The inherent ability of an animat model to accurately represent the individual and aggregate assessment of sound exposure has been well established (Frankel et al. 2002; Schecklman et al. 2011) and represents the basis for numerous environmental assessments including two global environmental impact statements (Department of the Navy 2001; NSF-USGS 2011). In these assessments, the resultant individual-modeled exposure levels of sound are compared with set criteria values to predict potential impacts. The attendant metrics and associated assessment criteria, whether physiological or behavioral in nature, may be further delineated by the spectral, temporal, and spatial properties of the sound field. In the absence of site-specific animal location and movement data, setting stochastic limits for both animal characteristics (e.g., distribution and dive profiles) and the environment (e.g., ambient noise) can bound the modeled estimate of net exposure. Where the stochastic bounds are well supported by documented site and seasonal field measurements, the accuracy of the modeling is considerably improved. Recent studies have further highlighted the importance of the context of the acoustic exposure to the likelihood and degree of the behavioral response (Ellison et al. 2011). Context can affect changes in diving and movement behavior as well as vocalization pattern (DeRuiter et al. 2013; Goldbogen et al. 2013). The need to emulate field observations requires systematic modeling techniques for all aspects of the study from source characterization and movement to animal behavior both in the planning stage and in support of the evaluation of the results. The key focus of this paper is to extend the stochastic approach to key contextual variables, especially the effect on sound exposure if an animal averts from a given received level of sound as well as the effectiveness of passive acoustic monitoring (PAM) systems for determining animal presence and relative location during monitoring and mitigation applications.

2 Stochastic Modeling

There are two main complicating factors attendant to the virtual modeling of the spectral, temporal, and spatial properties of both sound sources and marine wildlife. The first of these is that the sound field is inherently complex, including time, range, and depth dependence due to varying environmental conditions and source characteristics. These factors influence all aspects of the propagating acoustic field. Furthermore, the behavior of marine animals differs greatly between taxa, resulting in different animals sampling a given acoustic field in different ways. For example, consider a source in an acoustic surface duct environment. Animals that spend the majority of their time at depths below the surface duct will sample that surface duct less frequently than an animal that dives more shallowly and surfaces more often. Thus both the maximum sound pressure level (SPL) and the sound exposure level (SEL) for the shallow diver are likely to be greater than that for the deeper diver. Both the sound field and animal behaviors can be considered with two key modeling tools, an animal distribution and movement model integrated with a high-resolution acoustic propagation model (e.g., Frankel et al. 2002). The typical output of such models is an exposure history for each animal based on the acoustic source(s) and the animals moving through space and time in the model. Every time the acoustic source transmits, a received level (RL) for the modeled animal is, or should be, calculated. These exposure histories, one for each modeled animal, are the primary output of such a model.

These exposure histories can be used to predict potential impacts based on appropriate metrics. Metrics for sound exposure have included maximum SPL and, more recently, SEL (Southall et al. 2007). However, when the effect of interest is the behavioral response of an animal to the acoustic exposure, one must take into account more than just the absolute received level of the sound but also the relative metrics such as signal-to-noise ratio and sensation level as well as other contextual factors (Ellison et al. 2011).

Given this degree of complexity in modeling both animal behavior and sound sources, one method of bounding the results is to employ a stochastic approach to define the limits of the key metrics (Table 38.1). An analysis of the influence of various metrics in four modeling scenarios includes exposure assessment, acoustic aversion, PAM, and a multisensor visual-passive acoustic line transect survey.

Table 38.1 Stochastic variables in acoustic modeling applications

Applications	Key modeling features	Stochastic variables
	Animal distribution and movement by species and behavioral state	Movement and dive pattern Hearing physiology
Exposure assessment		Ambient noise Water column physics Bottom properties
	Establish sound level aversion matrix	Probability of aversion as function of exposure Sound pressure level
Acoustic aversion (or attraction)	Postaversion response	Direction/dive pattern/speed Change in vocalizations
	Postaversion recovery	Evaluate level/distance/time
	Vocalization behavior and resultant sound field	Spectrum, source level Repetition rate
PAM evaluation	Background noise	Sea state and anthropogenic noise
	Acoustic receiver and processing parameters	Array type, location, and depth System processing gains and detection threshold

PAM passive acoustic monitoring

2.1 Exposure Assessment

In an acoustic-exposure assessment, the spatial, temporal, and spectral nature of the sound sources and the distribution and behaviors of potentially affected marine wildlife are modeled with the best available measured data. This produces a time-varying three-dimensional matrix of the ensonified environment and a corresponding animal location matrix. The discrete integration of these two modeled matrices over time is typically accomplished by using a time step that supports Nyquist sampling, i.e., at a time step less than half that of the shortest animal movement parameter, often set at 30 s or less.

The two major components of this modeling approach that are amenable to an instructive stochastic approach are the animal movements and the sound field. Animal movement data are being compiled into comprehensive databases such as the Marine Assessment, Decision, and Planning Tool (Vigness-Raposa et al. 2011; Ellison 2012), providing measured information for the accurate modeling of parameters such as relative residency, dive patterns including near-surface respiration periods, and the general speed of movement. Each behavior is set to randomly sample between a minimum and a maximum value, although sampling can also be modeled with distributions other than normal if supported by measured data. Where species site and seasonal data such as dive patterns are available from tagged animals, the values are tuned to those results.

Transmission loss models used to predict the propagated sound field require many physical environmental descriptors such as sound velocity profile. These values can either be measured in situ or extracted from relevant databases (e.g., generalized digital environmental model [GDEM]; Naval Oceanographic Office (2003)). Background noise, bottom-loss properties, and surface-scattering losses can be accounted for stochastically using a range of expected values.

2.2 Acoustic Aversion

In a recent exposure assessment study, the 2008 fall migration of the bowhead whale population was modeled using the animat approach as the whales migrated past a series of industrial noise sources including seismic air gun activity, near-shore production sites, and ship noise (Streever et al. 2012; see Chapter 36 by Fleishman et al.). As part of this modeling study, animats were programmed to the probability of deflection from the sound sources at three SPLs (Table 38.2). The animats were in a generally westward migration path, a programmed behavioral rule; therefore, the animals tended to continue west after any deflection from shore boundaries or received sound levels.

In addition to the received level at which aversion might occur, three additional parameters of the aversion rule (probability of deflection, deflection angle, and time between RL checks) determine the degree and manner in which each animat will

Table 38.2 Bowhead deflection parameters

Received level, dB re 1 μPa rms SPL	Deflection angle, relative degrees	Probability of deflection	Time between SPL checks (s)
≥160	10	0.6	300
≥170	20	0.85	60
≥180	30	0.99	30

SPL sound pressure level, *rms* root-mean-square

respond over time. Once the RL threshold has been exceeded, the probability of deflection is the first parametric test that must be passed before the deflection behavior becomes active. It is perhaps the most influential parameter and the one that is best supported by field observations. Note that even though the probability of deflection at a SPL ≥ 160 dB was set at 60% (Table 38.2), the deflection condition was reevaluated every 5 min, making it more likely that an animat who bypassed this level would eventually hit a higher avoidance level and initiate a response at the next decision point. Compared with the same animat set with no aversion, the resultant distribution of the number of animats versus exposure levels varied substantially when both the maximum SPL and the cumulative SEL (CSEL) were considered (Fig. 38.1). Although this aversion example evaluated exposure assessment, the same approach would be useful in modeling the effectiveness of the soft start of a sound source in the presence of marine wildlife, a mitigation technique often required by industry (Johnson et al. 2007).

2.3 PAM

PAM systems are an important and often prescribed tool in a variety of environmental studies, especially for monitoring bioacoustic activity and performing acoustic monitoring and mitigation. These systems often are required to reliably detect a broad range of vocalizing animals at frequencies spanning 10 Hz–10 kHz and higher. They must also work under a variety of oceanographic conditions and in both natural and anthropogenic noise fields.

A PAM system's utility can be evaluated under these varied requirements before deployment through stochastic modeling of several key parameters (Table 38.1). Such a modeling exercise is presented here for a location off the Azores to evaluate the effectiveness of a towed array to detect sperm whale vocalizations. The PAM simulation using the Acoustic Integration Model (AIM) is shown in Fig. 38.2 and shows the path of the towed-array configuration in relation to the vocalizing whales. In this snapshot of the scenario, whale A is depicted vocalizing nominal 400-Hz clicks at a depth of 1,000 m, with a source level (SL) set to 190 dB re 1 μPa at 1 m (Goold and Jones 1995). Dive profiles and time at depth were defined for two dive types: near-surface dives bounded by 0–10 m over 2–10 min, and deep dives of 200–1,500 m over

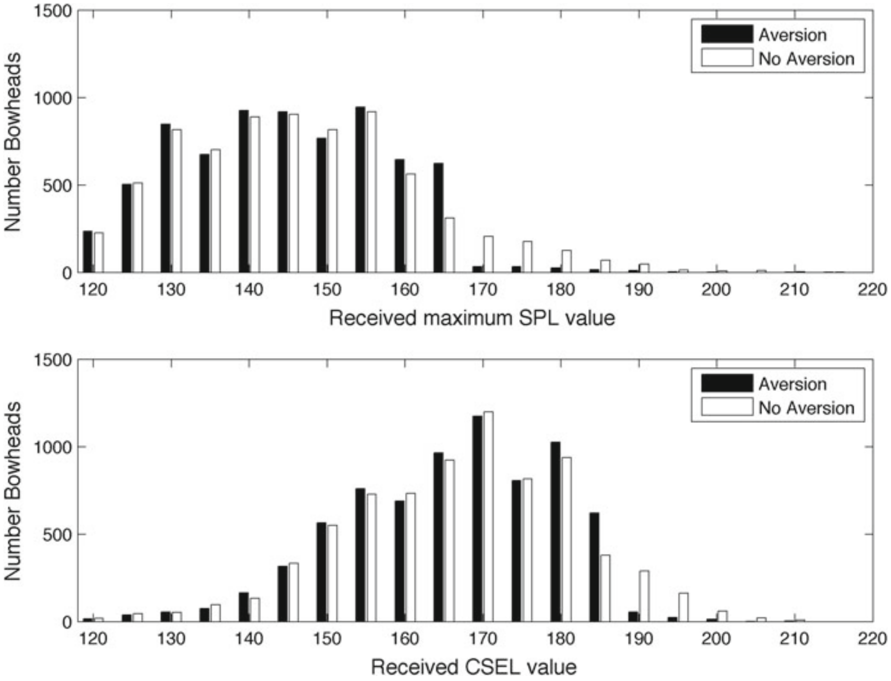


Fig. 38.1 Comparison of maximum sound pressure level (SPL) values and cumulative sound exposure level (CSEL) values for whales that were programmed to avert versus the same animat set with no aversion

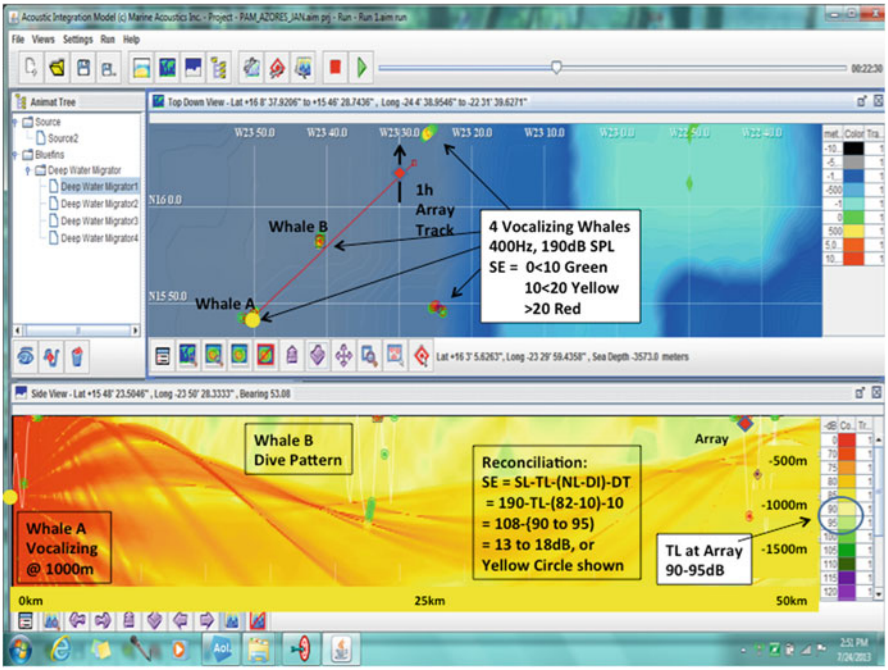
10–40 min at depth. Animat speed varied between 3 and 10 km/h and course changes varied up to ±90°. The vocalization rate was nominally set at 6/min.

All values including noise level (NL) were calculated for the 1/3-octave band encompassing 400 Hz, the fundamental frequency of the sperm whale vocalizations used for this example. In this instance, the SE of each vocalization was determined by the following sonar equation formulation

$$\mathrm{SE} = \mathrm{SL} - \mathrm{TL} - (\mathrm{NL} - \mathrm{DI}) - \mathrm{DT}$$

where TL is the one-way transmission loss at 400 Hz from whale location to the array, NL is the 1/3-octave band (sea state 2 equivalent selected for this example), DI is the array directivity index (set here at 10 dB), and DT is the system detection threshold (set here at 10 dB).

SE values are plotted on the two views: (1) animat location in plan view (latitude and longitude) and (2) animat location in side view (depth and range plotted over a TL plot). The snapshot shown is when one of whale A's clicks was detected, indicated by a yellow circle corresponding to $10 < \mathrm{SE} < 20$ dB, and the array is represented by a red diamond. Using the color scale for TL at the array, the TL value lies between 90 and 95 dB, resulting in a SE between 13 and 18 dB, corresponding to the yellow circle of whale A vocalizing at 1,000 m depth.



4 Vocalizing Whales
400Hz, 190dB SPL
SE = 0<10 Green
10<20 Yellow
>20 Red

Reconciliation:
SE = SL-TL-(NL-DI)-DT
= 190-TL-(82-10)-10
= 108-(90 to 95)
= 13 to 18dB, or
Yellow Circle shown

Fig. 38.2 Passive acoustic monitoring towed-array simulation of detecting vocalizing whales in the vicinity of the Azores. SE, signal excess; SL, source level; TL, one-way transmission loss at 400 Hz from whale location to the array; NL, 1/3-octave band noise level; DI, array directivity index (set here at 10 dB); DT, system detection threshold (set here at 10 dB). Color code represents the SE of the calls at the passive acoustic monitoring array in 10-dB increments. *Red diamond* is the source of the path of the towed-array configuration

A similar modeling result can be constructed for different array designs, tow depths, and ambient-noise conditions to determine overall capability. Examining the SE equation, it is clear that an increase of 10 dB in the noise band of interest through the presence of a nearby anthropogenic noise source would provide a substantially reduced number of detections with the array configuration shown.

2.4 Other Stochastic Modeling Applications

Using a similar approach, it is straightforward to extend this modeled PAM application to a combined visual/acoustic/radar line transect by adding the system capabilities for observers and radar as a function of limiting sea states and animal surface behavior for visual and radar target strength. Extension to modeling an active sonar working as a mitigation and monitoring system is also an existing capability requiring only the aspect-dependent target strength of the animals as a function of frequency and calculation of two-way TL.

Conclusions

The animat modeling techniques illustrated here can be adapted to a wide range of monitoring and mitigation scenarios using known system parameters. Modeling overall performance of such systems can evaluate effectiveness by varying components of the scenario. The increase in the number of well-structured behavioral-response studies with tagged animals also provides new data to support the modeling of not only initial reaction characteristics but also follow-on changes in movement, dive patterns, and vocalization rate related to the SEL.

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Chapter 39
Underwater Sound Levels at a Wave Energy Device Testing Facility in Falmouth Bay, UK

Joanne K. Garrett, Matthew J. Witt, and Lars Johanning

Abstract Passive acoustic monitoring devices were deployed at FaBTest in Falmouth Bay, UK, a marine renewable energy device testing facility during trials of a wave energy device. The area supports considerable commercial shipping and recreational boating along with diverse marine fauna. Noise monitoring occurred during (1) a baseline period, (2) installation activity, (3) the device in situ with inactive power status, and (4) the device in situ with active power status. This paper discusses the preliminary findings of the sound recording at FabTest during these different activity periods of a wave energy device trial.

Keywords Renewable energy • Passive acoustic monitoring • Marine noise

1 Introduction

The extraction of renewable energy from the marine environment is a growing global industry, particularly in the United Kingdom and Europe. However, there is a lack of information on the sound produced from in situ wave energy devices during all stages of their deployment, operation, and decommissioning. Because anthropogenic underwater noise can negatively affect marine species (National Research Council 2003; Popper and Hastings 2009), this is an area requiring research.

The majority of the research on marine renewable energy and underwater sound has, so far, taken place within the offshore wind energy sector. Research on the sounds produced during operation of wave energy converters (WECs) has been highlighted as an area requiring research (Patrício et al. 2009). In situ underwater sound measurements have been taken from a seventh-scale wave energy prototype

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during operation, and it was found that the acoustic signature could be detected up to a distance of 1.5 km from the device in the absence of local shipping (Bassett et al. 2011). Underwater sound has also been recorded from a full-scale WEC in the Lysekil Research Park, Sweden, but this research was limited to sea conditions of wave heights <0.5 m (Haikonen et al. 2013). There is a lack of published research on the sound levels during installation activity and during varying sea states. Therefore, research in this area is critically needed to inform the consenting process.

A variety of device types exist, although the majority are point absorbers (World Energy Council 2010). The main sources of sound occurring from point-absorbing WECs are considered to be mooring noise, flexing joints, and rotating machinery noise (Richards et al. 2007). Installation, particularly mooring of the device, has been highlighted as the activity that is most likely to produce the loudest sound levels during the life cycle of a WEC (Patrício et al. 2009). The presence of other sources of sound, such as local shipping and weather, and site-specific acoustic propagation characteristics will affect the received sound levels (Ingenito and Wolf 1989). Additionally, for marine animals, the hearing sensitivity of the species will affect the received levels (Southall et al. 2007).

To address these knowledge gaps, sound recordings were made during the deployment, installation, and operational phases of a wave energy device trial in Falmouth Bay. The device monitored was a point-absorbing WEC with three power take-off (PTO) or power generation units, which were moored individually to the seabed.

2 Methods

2.1 Deployment Location

The WEC was deployed at the Falmouth Bay test site (FaBTest) site on the south coast of Cornwall, UK. The site is 2 km^2 in size, between 3 and 5 km offshore, and 20–50 m in depth.

Falmouth Harbour is a busy commercial port, with 1,309 ship arrivals reported in 2009 (Department for Transport 2010), which is the second highest in the southwest. The area also supports considerable recreational boating (Latham et al. 2012).

2.2 Data-Gathering Equipment

Two autonomous multichannel acoustic recorders (AMARs) generation 2 (JASCO Applied Sciences) were deployed in Falmouth Bay, alternately, on six occasions, two of which are reported on here, at a distance of ~200 m from the WEC. These devices use GeoSpectrum M8E hydrophones that have been calibrated by JASCO Applied Sciences. The AMAR was programmed to record for the first 30 min in every hour. Table 39.1 shows the deployment locations and equipment settings. The effective frequency range is 10 Hz to half of the sampling frequency.

Table 39.1 Deployment dates, locations, and equipment settings of the autonomous multichannel acoustic recorder

Deployment date	Position	Sampling frequency (kHz)	Deployment method
10 March 2012	50°099720′ N, 04°99639′ W	96	Dome
13 June 2012	50°098889′ N, 04°995278′ W	64	Flotation collar

There were two methods of deployment: the dome configuration and the flotation collar configuration.

For the dome method, the AMAR was attached to a custom-built steel frame along with an acoustically triggered pop-up buoy to allow retrieval and covered in a yellow plastic protective dome with an opening for the hydrophone. The frame was weighted and rested on the seabed.

For the flotation collar method, a flotation collar was attached around the AMAR that caused it to float in a vertical position in the water column. The AMAR was attached to the center of a weighted ground rope and was ~5 m off the seabed. Because there were different deployment configurations that could have affected the received levels (RLs), for example, the hydrophones were at different depths, the data were kept separate for analysis.

2.3 Site Activity Periods

The baseline period occurred immediately before the deployment of the WEC from 11 to 25 March 2012. Installation activity is considered to include all activities associated with the installation of the device and included the presence of work vessels on-site and the laying of the anchor chain. This activity took place intermittently from 26 to 30 March 2012. Comparison periods, when no installation activity was taking place, were chosen based on similarity in time and wave height to minimize differences in sound levels due to other factors.

Operational activity was considered to occur when one or more PTO systems were active and producing power as recorded by the device developer. This occurred intermittently between periods of nonoperational activity. All analyzed operational periods took place in the second deployment of the AMAR.

2.4 Data Processing

The acoustic data were calibrated using the hydrophone-response curves provided by JASCO Applied Sciences and an acoustic gain of 0 dB. MATLAB scripts were developed to process the WAV files. These include a fast Fourier transform (FFT) function using a 1-s Hann window with a 50% overlap performed for every file to provide the power spectral density (PSD) in decibels re 1 $\mu Pa^2\ Hz^{-1}$. A median PSD value was calculated per minute per hertz and stored. The median was used because the data exhibited a nonnormal distribution.

2.5 Wave Data

Wave height data were obtained from the Seawatch Mini II Directional Wave Buoy (Fugro 2010) deployed at the FaBTest site at a distance of ~334 m from the WEC. The wave buoy sampled at a frequency of 2 Hz for 1,028 s (17 min 4 s) every 30 min (Ashton et al. 2013). The data were processed using the proprietary software WaveSense to provide an average significant wave height value every 30 min (Harnois et al. 2013) from 10:00 am on 19 March 2012. Wave height was used to give an indication of the environmental contribution to the ambient-sound levels.

3 Results

3.1 Baseline Period

The sound levels during the baseline period exhibited high variability, especially at low frequencies. The average range (of minute averages) in the frequency range 10–100 Hz was 36.1 dB, with a maximum of 53.2 dB at 66 Hz. The variability of the sound levels decreased with frequency. The median range in the frequency band of 101–1,000 Hz was 29.6 dB and the median range in the frequency band of 1,001–10,000 Hz was 15.5 dB.

The median sound levels decreased from 10 to 54 Hz, with peaks at 26 and 43 Hz. The sound level then increased steeply to ~100 Hz, with a peak at 61 Hz. There was then a more gradual increase in sound levels, with maxima around 600 Hz. The sound levels then decreased with frequency at a rate of −2.1 ± 0.9 dB/one-third octave.

The mean significant wave height for the baseline period in which the wave buoy was deployed (19–25 March) was 0.77 ± 0.46 m. A correlation was found between the significant wave height and sound level in the frequency ranges of 10–100 Hz (Spearman's rank, $r = 0.63$, $P = 5.30 \times 10^{-18}$), 101–1,000 Hz (Spearman's rank, $r = 0.33$, $P = 3.85 \times 10^{-5}$), and 1,001–10,000 Hz (Spearman's rank, $r = 0.66$, $P = 1.68 \times 10^{-20}$) and in the whole frequency range of 10–48,000 Hz (Spearman's rank, $r = 0.67$, $P = 6.15 \times 10^{-21}$).

3.2 Installation

The mean significant wave height during the installation activity periods was 0.41 m and during the comparison periods, when no installation activity was taking place, was slightly higher at 0.47 m. The median difference for the whole frequency range (10–48,000 Hz) was 2.2 dB, with an interquartile range (IQR) of 0.8 dB. Table 39.2 shows the median differences for certain frequency ranges.

The maximum difference between the median sound levels during installation activity compared with no installation activity was 34.8 dB at 37 Hz and the minimum was 0.5 dB at 37,542 Hz.

Table 39.2 Difference between median sound levels during installation activity compared with periods when no activity was taking place

Frequency range (Hz)	Median difference (dB re 1 μPa)	Interquartile range (dB re 1 μPa)
10–100	18.53	7.10
100–1,000	13.31	3.62
1,000–10,000	4.43	2.88

During the first deployment of the sound recording device, the AMAR was 190 m away from the WEC, although the activities would have been taking place at varying distances. Assuming an intermediate transmission loss (TL) of $15 \log R$, where R is the distance of the receiver from the source, the TL was estimated to be 34.1 dB. The maximum RL that occurred 5% of the time was 120.4 dB at 176 Hz. The sound level at the source was therefore 154.5 dB at 176 Hz at 1 m 5% of the time.

3.3 Operation

The number of 30-min files for the nonoperational periods was 1,430 compared with 100 for operational periods. During operational periods, an increase in sound levels compared with those in nonoperational periods was observed in the frequency ranges of 45–69 Hz, 74–79 Hz, and 89–112 Hz; frequencies around 1,433 and 1,966 Hz; and frequencies >6 kHz, with a maximum of 3.8 dB at 58 Hz. The other peak frequencies with differences >0 dB were 51, 54, 93, and 19,641 Hz.

The sound levels were quieter during nonoperational activity in the frequency ranges of 10–44 Hz, 65–73 Hz, 80–88 Hz, 113–1,325 Hz, 1,522–1,916 Hz, and 2,659–5,834 Hz and around 19,521 Hz, with a maximum difference of −8.8 dB at 15 Hz. The median difference was −0.7 dB in the frequency range of 10–5,000 Hz and 0.7 dB for the whole frequency range of 10–32,000 Hz.

4 Discussion

4.1 Baseline Period

Ships are often at anchor in Falmouth Bay with their generators running continuously, which adds to the noise from shipping movements. Shipping has been found to significantly affect the sound levels in Falmouth Bay and this was found to be mostly below 1 kHz (Merchant et al. 2012). This is in agreement with the highly variable sound levels found below 1 kHz during the baseline period.

The baseline sound levels exhibit a maxima in the region of 100–1,000 Hz and decreasing sound levels of -2.1 ± 0.9 dB/one-third octave (Fig. 39.1), which approximately agree with the trends suggested by Wenz (1962). However, the declining trend between 10 and 52 Hz is in contrast to the general trends presented by Wenz

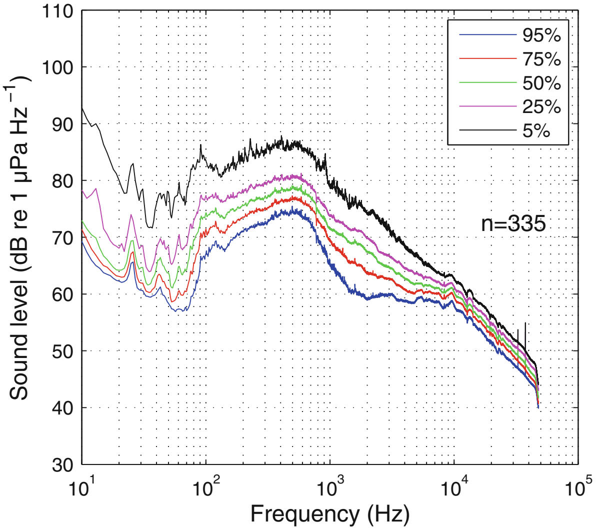

Fig. 39.1 Sound level percentiles during the baseline period (11–25 March 2012)

(1962) and may indicate atypical high sound levels above this frequency and particularly above 100 Hz. This is in-line with the high levels of shipping in the area.

Although wind is more closely related to ambient-sound levels than sea state or wave height (Cato and McCauley 2002), wave height data are available in close proximity to the AMAR and WEC and have been shown to correlate with sound levels. Wave height is, therefore, used as an indication of the environmental contribution to sound levels.

4.2 Installation

Installation activity was found to increase sound levels by a median of 8.2 dB in the range of 10–5,000 Hz. The average wave height during the comparison period was higher than during the periods of activity (by +0.06 m) so it is considered unlikely that weather sound contributed to the difference in sound levels. It is possible that other sources of sound such as shipping activity could have contributed to the difference. In agreement with the projection from Patrício et al. (2009), the highest sound levels have been found to occur during installation activity.

The frequency of the loudest sounds during installation is considered to be below the optimal hearing range for cetaceans but within the hearing range of some species of fish (Chapman and Hawkins 1973; National Research Council 2003; Kastelein et al. 2008). It is possible that this sound level (154.5 dB at 176 Hz at 1 m 5% of the time) could cause a physiological or behavioral response in fish, including a temporary threshold shift (TTS) at close proximity to the source.

Scholik and Yan (2002) found a TTS in *Pimephales promelas* (fathead minnows) after playing boat noise at 142 dB for 2 h. Sound levels here were found to be

>142 dB 5% of the time at 23 frequencies between 141 and 491 Hz. However, 5% of the installation time is equivalent to around 34 min, which occurred intermittently over 5 working days and may not be of a duration to cause a TTS. Peak sound levels are currently being further investigated. Additionally, fish gain important information about their environment from the soundscape so the masking of other sounds may be important (Popper and Hastings 2009).

4.3 Operational Activity

The sound levels during operational activity were not compared with those during the baseline period because the AMAR was deployed using different deployment configurations that may have affected the RLs. Using the dome configuration, the hydrophone was on the seabed, whereas, using the flotation collar configuration, the hydrophone was floating off the seabed at a height of ~5 m.

Sound levels during power production were found to be greater than during periods of nonoperation at some frequencies in the frequency range of ~50–100 Hz, around 1,433 and 1,966 Hz, and at frequencies >6 kHz (Fig. 39.2). The WEC is therefore

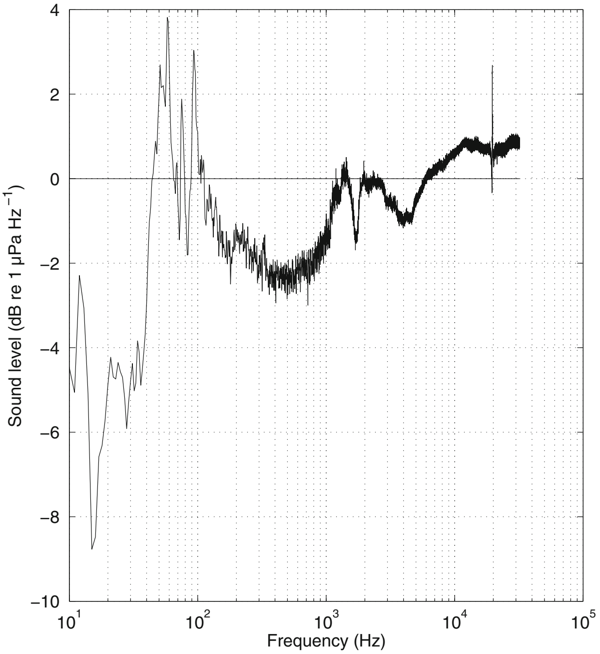

Fig. 39.2 Difference in sound levels between operational and nonoperational periods (June to August 2012). The *horizontal line* at $y=0$ indicates no difference. Peaks above *line* show frequencies for which the median sound level is louder during operational activity. Peaks below *line* show frequencies for which the median sound level is quieter during operational activity compared with nonoperational activity

considered likely to be producing sounds within these frequencies. It is possible that there are other sources of sound also contributing to this difference, which is currently being further investigated.

During monitoring of an operational full-scale point-absorbing WEC in Sweden, it was estimated that it wouldn't be possible to detect the sounds produced at distances >150 m (Haikonen et al. 2013). The hydrophone was ~200 m from the WEC in this study so it is possible that the sounds from the WEC are undetectable above the background noise at this distance. However, given the specific frequencies found to be louder during operational activity, this is considered unlikely, although it is being further investigated. Additionally, Bassett et al. (2011) found that the acoustic signature from an operational seventh-scale WEC could be detected up to 1.5 km away in the absence of local shipping. No acoustic signature has been detected from the WEC at FaBTest. However, it is possible that there are no periods without local shipping or ship generator noise given the busy nature of Falmouth Harbour.

5 Conclusions

The sound levels in Falmouth Bay are variable and affected by local shipping as well as by natural sources such as weather conditions and marine organisms. Installation activity was found to considerably increase the local sound levels, with a median difference of 8.5 dB re 1 $\mu Pa^2\ Hz^{-1}$ (10–5,000 Hz). It is challenging to assess the effect of the WEC in a variable ambient-noise environment, but it is possible that operational activity of the WEC raises the local sound levels at certain frequencies.

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Chapter 40

Predicting Anthropogenic Noise Contributions to US Waters

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Abstract To increase understanding of the potential effects of chronic underwater noise in US waters, the National Oceanic and Atmospheric Administration (NOAA) organized two working groups in 2011, collectively called “CetSound,” to develop tools to map the density and distribution of cetaceans (CetMap) and predict the contribution of human activities to underwater noise (SoundMap). The SoundMap effort utilized data on density, distribution, acoustic signatures of dominant noise

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sources, and environmental descriptors to map estimated temporal, spatial, and spectral contributions to background noise. These predicted soundscapes are an initial step toward assessing chronic anthropogenic noise impacts on the ocean's varied acoustic habitats and the animals utilizing them.

Keywords CetSound • SoundMap • Noise • Anthropogenic • Soundscape • Background

1 Introduction

The ocean is an incredibly efficient conductor of sound, allowing acoustic waves to propagate over vast distances (Munk et al. 1994). The acoustic environment or soundscape resulting from the accumulation of near and far sources is an integral component of the physical and biological habitats on which many aquatic animals that have evolved over millions of years rely. Sound often plays an essential role in various critical activities for these animals, such as breeding, foraging, maintaining social structure, and avoiding predators. In just the last ~100 years, however, human activities have caused large increases in introduced noise and fundamentally altered the nature of underwater soundscapes (Andrew et al. 2002; McDonald et al. 2006; Hildebrand 2009).

Initially, concern was primarily focused on the potential acute effects of sound sources that could lead to very near-term consequences (e.g., behavioral changes, strandings, direct physical harm). In recent years, however, there has been a distinct broadening of the focus to include the much larger scale and longer term chronic effects of increases in ocean noise and changes in underwater soundscapes, leading to a decreased ability of marine organisms to communicate with one another and to use sound to sense their environment (National Research Council 2003). An increasing number of scientific and management efforts (e.g., International Quiet Ocean Experiment, European Union Marine Strategy Framework Directive) more clearly directed at addressing chronic noise reflect this increased attention and highlight the importance of soundscape characterization, modeling, and mapping (Boyd et al. 2011; Dekeling et al. 2013). The National Oceanic and Atmospheric Administration (NOAA) has similarly recognized the need for this work through the convening of the cetaceans and sound (CetSound) project in which it is developing an underwater sound field and cetacean density and distribution mapping tools.

2 Cetsound Working Groups

In January 2010, through a letter to the President's Council on Environmental Quality, then NOAA Administrator Dr. Jane Lubchenco committed to improving the tools used by the agency to evaluate the impacts of man-made noise on cetacean species.

As a result of this commitment, two data- and product-driven working groups were convened in January 2011: the Underwater Sound-Field Mapping Working Group (SoundMap) and the Cetacean Density and Distribution Mapping Working Group (CetMap).

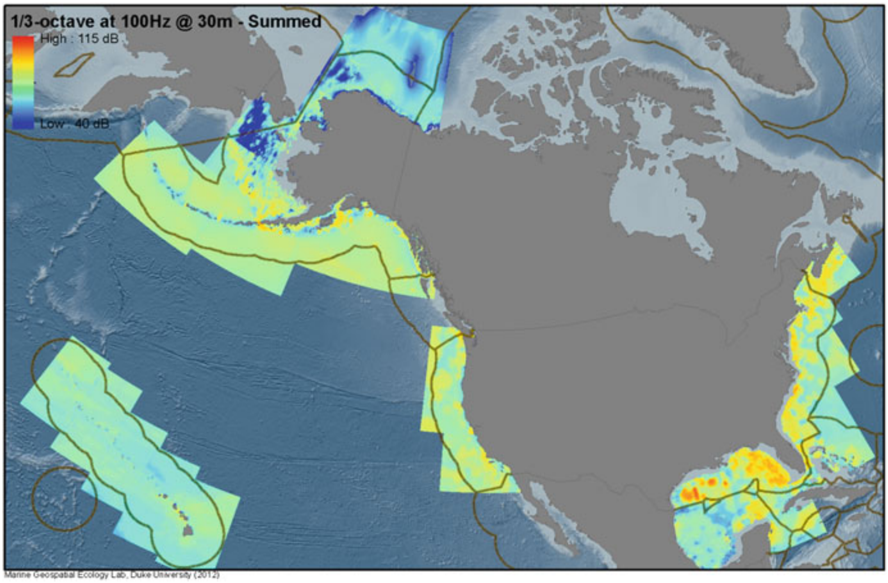
The CetMap was tasked with (1) creating regional cetacean density and distribution maps that are time and species specific, using survey data and models that estimate density with predictive environmental factors; and (2) augmenting these broader maps by identifying known areas of specific biological importance for cetaceans, such as reproductive areas, feeding areas, migratory corridors, and areas in which small or resident populations are concentrated. The SoundMap (the focus of this paper) was tasked with creating mapping methods to depict the temporal, spatial, and spectral characteristics of underwater noise. On 23–24 May 2012, at a symposium in Washington, DC, the draft CetMap and SoundMap products were presented to an audience of ~170 people that included participants from government agencies, regulated industries, independent scientists, environmental consultancies and conservation advocacy groups (National Oceanic and Atmospheric Administration 2012). The final report from the symposium as well as both SoundMap and CetMap products can be accessed on the project Web site (http://cetsound.noaa.gov).

The positive response to this symposium has led to a follow-up effort to develop a long-term NOAA ocean noise strategy to guide how NOAA approaches the issue of ocean noise in the future. More information can be found on the CetMap Web site and the developing NOAA ocean noise in Chapter 48 by et al. Here, we provide more detail on the SoundMap portion of the project, describing its predictions for anthropogenic noise contributions within US waters.

3 SoundMap Chronic Noise Predictions

The objective of the NOAA SoundMap was to develop mapping methods to depict temporal, spatial, and spectral characteristics of underwater noise resulting from dominant anthropogenic sound sources. Heat, Light and Sound Research, Inc. (HLS), was contracted to assist tool-building efforts and undertake the extensive sound-propagation modeling in coordination with the efforts and guidance of the working group. The sound mapping tools use environmental descriptors (e.g., bathymetry, sea surface roughness, bottom composition, sound speed profiles) and available data on the distribution, density, and acoustic characteristics of human activities within US waters (e.g., data from World Meteorological Organization Voluntary Observing Ships Scheme [VOS] for global shipping, NOAA Fisheries Observer database for fishing activity, Bureau of Ocean Energy Management [BOEM] data on seismic surveys) to develop first-order estimates of their contribution to background noise levels at multiple frequencies, depths, and spatial/temporal scales.

The effort focused on developing feasible methods that could be implemented within the 1-year time frame of the CetSound working groups. To achieve this, throughout the process, a variety of informed approximations and assumptions were therefore made to increase computational feasibility and to bridge data gaps. All extrapolations and assumptions made in developing these products have been explicitly documented in methodology summaries that are available online. An overview of the regions throughout the US exclusive economic zone (EEZ) where sound field maps were produced is shown in Fig. 40.1, with a listing of the source types and events modeled within each region in Table 40.1.



Marine Geospatial Ecology Lab, Duke University (2012)

Fig. 40.1 Overview map showing representative sound-field maps produced throughout the majority of US exclusive economic zone waters

Table 40.1 Overview of mapping effort: regions, type of soundscape modeling that was undertaken (long-term chronic or exemplar acute event), and the sources used in the modeling

Region	Chronic noise/ event modeling	Anthropogenic activity
Arctic	Chronic	Global shipping, passenger vessels
	Event	Beaufort—multiple seismic surveys
Gulf of Mexico	Chronic	Seismic surveys, rig support vessels, global shipping, passenger vessels
	Event	Rig decommissioning event
North Atlantic US EEZ	Chronic	Global shipping, passenger vessels
	Event	Cape Cod wind farm installation/construction
North Atlantic Basinwide	Chronic	Global shipping, passenger vessels
North Pacific US EEZ	Chronic	Global shipping, passenger vessels, fishing vessels
	Event	Hawai’i—Navy active sonar training exercise
North Pacific Basinwide	Chronic	Global shipping, passenger vessels

EEZ exclusive economic zone

3.1 Spectral Resolution

The emphasis of SoundMap modeling on broad-scale and long-term (seasonal-to-annual) noise exposure resulted in a focus on low frequencies, ranging from 50 to 1,000 Hz (with several specific exceptions), because higher frequencies are subject to strong absorption effects and are more local in effect. Broader band levels (1/3-octave) were estimated based on modeled frequencies to assist interpretation relative to mammalian hearing systems.

3.2 Spatial Resolution

SoundMap modeling focused on coastal waters at least 5 m in depth out to the 200-nm US EEZ boundary at a 0.1° × 0.1° (~100 km^2 at the equator) grid size. Additionally, due to the emphasis on low frequencies and the lack of a hard boundary for noise at 200 nm, some sources of chronic noise at greater ranges were modeled for larger portions of the ocean basins at 1° × 1° (~10,000 km^2 at the equator). To capture differences in sound propagation and how this can influence interactions with marine wildlife that spend time at different depths, modeling was conducted at discrete depths between 5 m and (up to) 1,000 m.

3.3 Temporal Resolution

The central SoundMap products are predicted noise-level maps for US EEZ waters of the continental United States, Hawai'i, and Alaska (overview in Fig. 40.1). These maps depict predictions of wide-ranging contributions from "chronic" anthropogenic sources of underwater noise, including vessels (merchant shipping, ocean-going passenger vessels, and midsized service, fishing, and passenger vessels in regions where data were available) and sustained areas of offshore energy exploration (seismic surveys). Predicted received levels are expressed as equivalent, unweighted sound pressure levels (SPL_{eq}), which are averages of aggregated sound levels. Averaging time varies according to the appropriate timescales for the activities of interest, with a focus on annual averages from year-round activities (e.g., merchant shipping in most regions) and shorter scales for activities or events that are seasonal (e.g., in sometimes ice-covered areas).

4 Event Scenario Modeling

Although the primary focus of the SoundMap work was on predicting chronic noise introduced into the US EEZ, mapping efforts were also conducted for four localized and transient events that are more episodic or seasonal in nature. These were selected to reflect major acute sources of man-made noise in areas of biological importance to marine mammals and included (1) a military active sonar training exercise in Hawai'i; (2) a period of seismic exploration in the Beaufort Sea; (3) the installation of an alternative energy platform off New England; and (4) the decommissioning of an oil platform in the Gulf of Mexico.

Due to the vastly different temporal scales covering the chronic noise and the event scenario modeling, the working group held key discussions on how to sum energy from chronic and intermittent sources during each of the transient event scenarios and present cumulative energy averages over days to months when some sources were intermittent during those time periods. The intent was to avoid averaging over "dead periods" between noisy events (especially very long events) and not retaining duration information, given the ultimate goal of integrating this meaningfully with the animals utilizing these habitats. Thus, events were divided into appropriate number of acoustic "states" characterized by combinations of sources that are coincident over discrete time periods (i.e., staging before driving a pile, then driving a pile, then a break, then driving a pile, etc.). Duration information associated with these states can be retained and exemplary output maps can be created for each.

5 Conclusions and Future Work

The SoundMap focused on developing a first pass at quantitative tools that could support the management of cumulative footprints from multiple chronic, lower intensity source types over large geographic scales and long time frames. The soundscape predictions produced by the this working group are an initial attempt to predict the contributions that man's activities make to the background underwater noise present in the US EEZ, with the intent of incorporating these types of predictions into future assessments of the impacts of chronic noise on marine fauna. Although the inherent restrictions of a 1-year working group effort led to clear limitations on what was feasible in this time frame and simplifying the assumptions to accomplish this, the results do illustrate the pervasiveness of sound from man's activities throughout the US EEZ. For the future, the working group did identify multiple needs to expand these tools and refine their results. Further development of these tools should include improving inputs on the distribution and density of anthropogenic activities and their associated acoustic signatures (level and spectral composition), utilizing more refined environmental descriptors (e.g., bottom composition, wind and wave conditions, sound speed profiles), incorporating additional anthropogenic sources, accounting for natural noise sources and ambient levels, and perhaps most critically, ground truthing predicted noise with empirical measurements.

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Chapter 41
Auditory Sensitivity and Masking Profiles for the Sea Otter (*Enhydra lutris*)

Asila Ghoul and Colleen Reichmuth

Abstract Sea otters are threatened marine mammals that may be negatively impacted by human-generated coastal noise, yet information about sound reception in this species is surprisingly scarce. We investigated amphibious hearing in sea otters by obtaining the first measurements of absolute sensitivity and critical masking ratios. Auditory thresholds were measured in air and underwater from 0.125 to 40 kHz. Critical ratios derived from aerial masked thresholds from 0.25 to 22.6 kHz were also obtained. These data indicate that although sea otters can detect underwater sounds, their hearing appears to be primarily air adapted and not specialized for detecting signals in background noise.

Keywords Sea otter • Hearing • Audiogram • Noise • Masking

1 Introduction

Sea otters (*Enhydra lutris*) are amphibious coastal-living marine mammals that have faced numerous obstacles on their path to population recovery since being hunted to near extinction in the late nineteenth century. Despite international protection (Kenyon 1969) and "red" listing by the International Union for Conservation of Nature (2013) as an endangered species, some populations remain threatened and are considered vulnerable to a variety of environmental and anthropogenic pressures. Their dependence on restricted nearshore habitats also puts sea otters at risk for acoustic disturbance from activities occurring both on land and at sea. Growing concern about human-related impacts has led to intense and multidisciplinary efforts to improve the overall knowledge of this sensitive species. Although targeted research has been recognized as fundamental to their long-term recovery (US Fish and Wildlife Service 2003), the potential effects of anthropogenic noise on sea otters are not well understood, in part because their auditory biology has never been studied.

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In this psychoacoustic study, we investigated the auditory sense of sea otters by describing absolute hearing capabilities in quiet aerial and underwater environments. Sea otter hearing was also evaluated in a masking scenario to understand how baseline capabilities are altered by the simultaneous presence of noise. This study extends previous work conducted with sea otters in our laboratory, which provided estimates of the frequency limits of aerial hearing (Ghoul and Reichmuth 2012).

2 Assessment of Amphibious Hearing Capabilities

Aerial and underwater hearing profiles (audiograms) for the sea otter were obtained for a 14-year-old adult male southern sea otter (*Enhydra lutris nereis*) living in captivity (USGS 2788-97R). The otter was trained to perform an auditory go/no-go detection task that involved positioning at a listening station and responding to the presence of a tone with a nose touch to a response target (correct detection) and remaining motionless in the absence of a signal (correct rejection). A favored food reward was delivered to the sea otter after each correct response. During experimental sessions, the amplitude of the acoustic stimulus was progressively altered using an adaptive, up-and-down method. Hearing thresholds at each sound frequency were determined at the 50% correct detection level averaged across multiple sessions with a stable performance. The subject's response bias (i.e., the likelihood of false positives occurring during signal-absent trials) was maintained above 0% and below 30% throughout testing. This allowed for direct comparison of auditory thresholds obtained at different frequencies as well as between media (air and underwater).

2.1 Aerial Audiogram

The testing environment used during the aerial hearing assessment was a hemianechoic acoustic chamber specially designed for marine mammal audiometry (Reichmuth et al. 2013). At the beginning of each session, the sea otter voluntarily entered the chamber and positioned himself in front of a listening station to initiate testing. The acoustic test stimuli were frequency-modulated (FM) tones of 500 ms with a rise/fall time of 20 ms. These signals had narrow frequency bandwidths of 10% (approximately 1/8 of an octave) and were centered on the following 12 frequencies: 0.125, 0.25, 0.5, 1, 2, 4, 8, 16, 22.6, 32, 38.1, and 40 kHz. The temporal, spectral, and amplitude characteristics of the test signals were measured before every session. Background noise in the acoustic chamber was measured after each session. A test session typically comprised 30–45 trials and lasted 12–15 min. A minimum of three sessions showing stable performance was required for final threshold estimation at each frequency, which was determined from the three-session average.

The aerial audiogram for the sea otter, showing hearing threshold as a function of frequency, is in Fig. 41.1, left. Aerial hearing was most sensitive at 8 kHz, where the lowest threshold of −1 dB re 20 μPa was measured. The range of best sensitivity (defined as the frequency range audible at 10 dB above the lowest threshold)

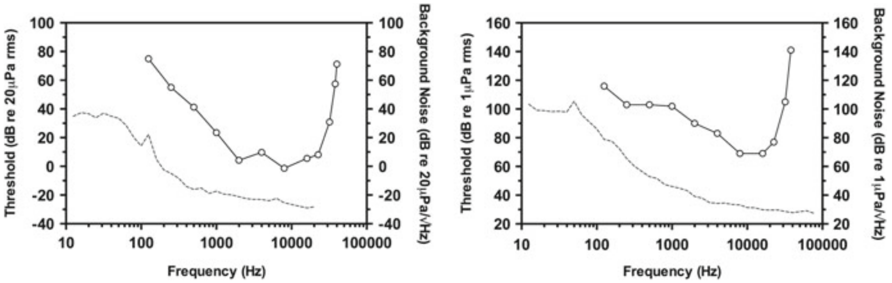

Fig. 41.1 Amphibious hearing profiles for a southern sea otter obtained using a psychoacoustic procedure. *Left*: Aerial audiogram showing absolute auditory detection thresholds plotted as a function of sound frequency. *Right*: Underwater audiogram with corresponding background noise, measured in the seawater testing pool. *Dashed lines*, acoustic background noise in the hemianechoic testing room. *rms* root-mean-square

extended from ~1.6 to 22 kHz. The subject's functional hearing range (defined as the range of audible frequencies at 60 dB) extended from 0.25 to 38 kHz. The audiogram determined for this sea otter had a typical U-shape, with a gradual roll-off in sensitivity on the low-frequency end (~18 dB/octave), and a sharp roll-off on the high end (~23 dB within a half-octave). Noise spectral density levels in the testing chamber (Fig. 41.1, left) decreased with increasing frequency, with levels dropping below 0 dB re 20 μPa/$\sqrt{}$Hz at frequencies above 0.25 kHz. The testing environment was sufficiently quiet to preclude influence by ambient noise.

2.2 *Underwater Hearing Sensitivity*

The methods used to test the sea otter subject's underwater hearing (i.e., sound generation and measurement, ambient-noise monitoring, psychophysical procedure, and final threshold determination) were similar to those used during aerial testing, with a few exceptions. The underwater hearing assessment was conducted in an acoustically mapped pool filled with seawater. The sea otter was trained to dive to an underwater listening station located 0.5 m below the surface where he performed the same go/no-go signal detection procedure as described in Section 2. To control for buoyancy effects, the otter was trained to maintain a vertical posture at the underwater listening station (i.e., oriented in a downward position) by using forepaw grips to stay submerged and hold his head in a fixed location. The acoustic stimuli and calibration procedures used during underwater testing were identical to those used for aerial testing. Testing occurred at 11 frequencies: 0.125, 0.25, 0.5, 1, 2, 4, 8, 16, 22.6, 32, and 38.1 kHz, with sounds projected from underwater transducers that were positioned to minimize spatial variability in the received sound field. Final absolute detection thresholds at each frequency were also determined in the same manner as for aerial testing, from an average of three thresholds obtained from individual test sessions.

The underwater audiogram for the sea otter subject is shown in Fig. 41.1, right. The subject's hearing was most sensitive at 8 and 16 kHz, where measured thresholds were the lowest at 69 dB re 1 μPa. The range of best sensitivity in water spanned ~4.5 octaves, from 4 to 22.6 kHz. The roll-off in high-frequency hearing was typically steep and had a 28-dB increase within a half-octave frequency step. Low-frequency hearing (0.125–1 kHz) was notably poor. The sea otter was unable to detect signals below 100 dB re 1 μPa within this frequency range. Noise spectral density levels in the underwater testing enclosure were sufficiently low to ensure that the measured thresholds were not influenced by background noise, especially at frequencies above 0.5 kHz, where noise levels were below 60 dB re 1 $\mu\text{Pa}/\sqrt{\text{Hz}}$.

3 Aerial Critical Ratios

The auditory masking experiment was conducted in the same hemianechoic chamber as described in Section 2.1. Masked aerial thresholds were measured at eight frequencies: 0.25, 0.5, 1, 2, 4, 8, 16, and 22.6 kHz. The test signals were a subset of the same narrowband FM sweeps used to measure the aerial audiogram. The maskers consisted of spectrally flattened, octave-band noise centered at each of the eight frequencies that was projected continuously during the session from the same speaker used to project the test signals. Depending on the frequency, the spectral density level of the noise was either 10 or 20 dB above the subject's absolute threshold. The procedure used to measure masked hearing thresholds was similar to that used during absolute audiometry, except that the sea otter was trained to perform the signal detection task in the presence of continuous noise.

Critical ratios, calculated as the difference (in dB) between the SPL of the masked threshold and the spectral density level of the surrounding masking noise, were obtained for the sea otter at frequencies from 0.25 to 22.6 kHz. The critical ratios for this sea otter are shown as a function of sound frequency in Fig. 41.2.

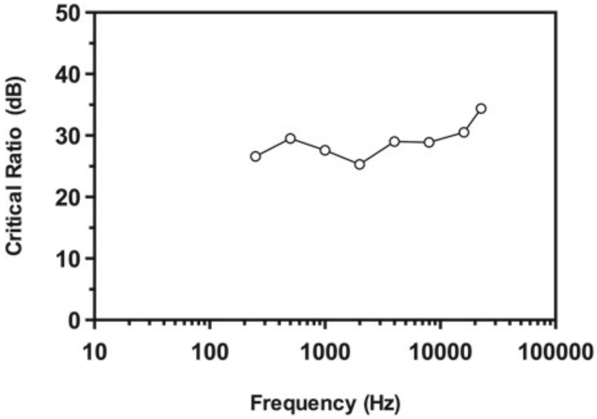

Fig. 41.2 Aerial auditory critical ratios for a southern sea otter are shown as a function of sound frequency

The masking data follow the same general trend as seen in other mammals tested, with critical ratios increasing gradually with increasing frequency. The lowest critical ratio estimated for this sea otter was 25 dB at 2 kHz, and the highest was 34 dB at 22.6 kHz. Below 2 kHz, the critical ratios were more variable with respect to frequency and higher than expected based on comparative data.

4 Conclusions

The amphibious auditory sensitivity profiles and critical ratios presented here for a trained sea otter represent the first hearing measurements for this species. Although these data were obtained from a single subject ($n = 1$), the results are consistent with the available audiometric data for terrestrial carnivores as well as with the preliminary estimates of the hearing range in sea otters (Ghoul and Reichmuth 2012). Specifically, our results indicate that although sea otters are adapted for an aquatic lifestyle and spend most of their lives at sea, they have retained acute aerial hearing sensitivity that is comparable to that of terrestrial carnivores such as the domestic ferret (Kelly et al. 1986) and least weasel (Heffner and Heffner 1985). Underwater, hearing is less sensitive than in other amphibious marine carnivores such as seals and sea lions (see Reichmuth et al. 2013). Perhaps most notable is the finding that low-frequency hearing is worse than expected in both air and water. The validity of these hearing measurements for one sea otter subject is supported by the ambient-noise data, which confirm that the hearing measurements obtained were not limited by background noise in the testing environments. Compared with other marine carnivores tested under similar masking conditions (e.g., see Southall et al. 2003), sea otters do not appear to be specialized for hearing under conditions of noise despite living in somewhat similar coastal habitats. Information gleaned from corresponding anatomical studies, which are ongoing in our laboratory, will be required to determine the manner and extent to which the sea otter auditory system is adapted for an amphibious lifestyle.

The results of this study will inform current conservation and management issues and can be applied to environmental assessment problems in a manner similar to that conducted with pinnipeds and other marine mammals (e.g., National Research Council 1994, 2000, 2003, 2005; Richardson et al. 1995; Southall et al. 2007). However, the relatively poor low-frequency hearing documented in this study is significant and worthy of further investigation because most anthropogenic noise in marine environments, including that related to transportation and oil and gas production, is generated at frequencies below 1 kHz.

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Chapter 42
Are Masking-Based Models of Risk Useful?

Robert C. Gisiner

Abstract As our understanding of directly observable effects from anthropogenic sound exposure has improved, concern about "unobservable" effects such as stress and masking have received greater attention. Equal energy models of masking such as power spectrum models have the appeal of simplicity, but do they offer biologically realistic assessments of the risk of masking? Data relevant to masking such as critical ratios, critical bandwidths, temporal resolution, and directional resolution along with what is known about general mammalian antimasking mechanisms all argue for a much more complicated view of masking when making decisions about the risk of masking inherent in a given anthropogenic sound exposure scenario.

Keywords Masking • Marine mammal • Risk model • Hearing • Regulation

1 Introduction

Masking is an effect of interfering environmental noise that is hard to detect and therefore hard to regulate. When does an animal fail to detect a signal as opposed to simply ignoring it? How often does a missed signal result in biologically meaningful consequences such as lost feeding opportunities or failure to detect a predator? Our appreciation for the consequences of signal masking by noise is based on our own personal experiences of masking in our own daily lives, giving the reality of the phenomenon and its potential consequences an immediate personal substance, but how easy is it to capture the complexities of masking and the many antimasking adaptations possessed by most animals?

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Recent models that have attempted to capture the potential risk of auditory masking in marine mammals exposed to man-made noise (Erbe and Farmer 1998; Clark et al. 2009) are based on a power spectrum model (PSM); when the noise energy within a specified band exceeds the signal energy, the signal is presumed to be masked (Patterson and Moore 1986). Erbe and Farmer (1998) and Clark et al. (2009) both offer refinements to the basic model but still fall short of the full range of variables known to contribute to signal antimasking. This leads to assumptions about the likelihood of masking from anthropogenic sound setting effective masking levels that may be 20–30 dB lower than is realistic for nondirectional ambient noise and 30–40 dB too low for discrete sources of noise. The corresponding estimates of areas that would be masked by a given sound source are therefore overestimated by 2–3 orders of magnitude or more, and reductions in the effective communication range are correspondingly overestimated to the same degree. Signal redundancy and active antimasking by signalers and receivers would reduce the likelihood of masking even more.

In this paper, I review the factors known to affect signal masking and some of the common antimasking features known to occur generally in a variety of species and thus are likely to occur in marine mammals if not, in fact, already demonstrated. Finally, I discuss potential alternative models of masking that might offer a better conceptualization of the risk of masking than existing models as well as a structure for modeling the potential biological consequences of such masking events.

2 Levels of Masking

The PSM and metrics of masking such as critical bandwidth address one form of masking: energetic masking in which the consequence is a failure to detect the signal. That is, the model is designed to assess the ability to detect a sound embedded within the overall soundscape consisting of a signal and other sounds or noise. Masking of signal identification or classification is presumed to take place under lower levels of masking noise than simple detection, but this becomes a problematic concept for the complex noise spectra and complex signals in most nonlaboratory scenarios that was well demonstrated by Erbe (2000). In both designed experiments and natural soundscapes, it can be difficult to determine which features of the signal are salient to the subject or how well the signal-processing systems of the animal can fill in gaps in signal information. Sounds can be correctly identified even when a great deal of the frequency structure or duration of the signal is masked, making the instantaneous likelihood of masking as predicted by something like a PSM a poor predictor of detection and correct classification of the biological signal of interest, especially if it is a highly redundant signal, as most biological signals are. A third level of masking, informational masking, can occur at even lower levels of masking noise. Informational masking is usually applied to the degradation by noise of a human subject’s ability to understand speech. A comparable analog for animals might be a successful recognition of a signal as being that of a conspecific (classification) but an inability to perform individual recognition or obtain other types of communication content that might be embedded within the structure of a signal.

Clark et al. (2009), for example, applied a value of as much as 18 dB additional signal energy beyond that required for simple signal detection based on some selected examples from the extensive and quite complex literature on human speech recognition. Clark et al. (2009) used a simple probability function to estimate the likelihood of correct signal interpretation ("communication") for signal excess above the threshold of detectability. Whether this is an appropriate correction factor for non-speech communication is difficult to determine but easily tested by psychophysical experiments with complex signals and noise like those employed by Erbe (2000) and Branstetter et al. (2013).

Under field conditions, initial decisions might be made on the basis of the potential attractiveness or aversiveness of the signal without risking further delays and then be updated by subsequent information (e.g., lack of further cues, cues getting louder). The point, for purposes of this discussion, is that simple detection masking may not be a sufficiently biologically relevant metric of masking for the purposes of assessing biological consequences and therefore effective regulatory guidance or action. The simplifying assumptions by Clark et al. (2009) about the difference between detection space and communication space likely overestimate that difference by using speech intelligibility as the communication threshold, but the addition of a factor beyond simple detection does help highlight a key source of uncertainty in any model attempting to capture the biological reality. The differences between detection threshold and communication threshold could be experimentally determined by training a subject to respond to any of a number of test sounds embedded in noise and then conducting the same test with signals requiring a differential response to each signal (e.g., matching to the sample).

3 Active Antimasking

Before moving to a discussion of antimasking mechanisms in the auditory processing chain itself, it is worth briefly noting the active antimasking mechanisms available to most vertebrates and probably to marine mammals as well, although demonstration that the observed phenomenon is a response to masking may be difficult in the wild where so many other uncontrolled variables may be affecting signal production and interpretation.

One of the best known active masking adaptations is the Lombard effect (Lombard 1911) in which both self-hearing and perception of environmental noise provide a feedback loop leading to the emission of louder signals, often with an accompanying upward frequency shift associated with the biomechanics of making a louder sound (Halfwerk and Slabbekoorn 2009). The phenomenon has been well demonstrated in a variety of nonhuman mammals (Brumm and Slabbekoorn 2005) and some marine mammals, i.e., beluga whales in the St. Lawrence River (Scheifele et al. 2005) and killer whales in Puget Sound (Holt et al. 2011). Active antimasking has also been posited as a possible explanation of a downward call frequency shift by blue whales in the eastern North Pacific (McDonald et al. 2009), even though the observed phenomenon does not follow the typical Lombard characteristics of animals producing louder calls that shifted upward in frequency. In humans, the

Lombard effect is accompanied by an increase in lung volume to power the louder signal and thus there is an increase in energy expended (Winkworth and Davis 1997). It remains to be determined whether the same processes apply to animals that vocalize during breathhold diving.

Others have also hypothesized that some marine mammals may have shifted the frequencies of their calls to place them above the ambient-frequency band with the greatest noise: right whales (Parks et al. 2007), beluga whales (*Delphinapterus leucas*; Lesage et al. 1998), and common dolphins (*Delphinus delphis*; Ansmann et al. 2007), although these reports lack the kind of evidence typically required for concluding that a Lombard effect is responsible for the observed change.

Off-frequency listening and detection of signal harmonics are other mechanisms by which animals can overcome masking. In off-frequency listening, the output of an auditory filter outside the band of interest, usually lower, may differentially reduce the input of the masker more than the signal, improving signal detection (Moore 2004). Because many biological sounds, including those of marine mammals, tend to have multiple harmonics beyond the formant or loudest harmonic, the availability of harmonics offers the opportunity to detect sufficient signal energy outside the band that is considered the "primary" or loudest frequency(ies). It is usually assumed that the loudest part of the signal is the primary frequency channel involved in signal sensory performance (e.g., in echolocation) or communication, but harmonics enable the signal to achieve the communication or sensory function in the presence of masking of the loudest harmonic(s). This is posited as one of the reasons why some echolocating odontocetes tend to use very broadband clicks for echolocation. Although echolocation signals need to be very short in duration to serve their sensory purpose and thus tend to be broadband by the nature of the signal waveform, the resulting broadband signals and echoes also provide antimasking benefits. Perhaps the most ubiquitous active demasking mechanism is signal redundancy. The emission of hundreds or thousands of clicks in a single prey pursuit by echolocating cetaceans, the seemingly incessant barking of sea lions on their rookeries and haulouts, and the prolonged song of humpback whales during the breeding season are the most obvious examples of this phenomenon in marine mammals. There is evidence that marine mammals actively increase redundancy, repetition, and call duration in the presence of noise (Lesage et al. 1998; Buckstaff 2004; Foote et al. 2004).

A central issue, both for understanding how much redundancy is "too much" energetically and in terms of anthropogenic impacts, is how much signal repetition costs the animal in terms of daily energy, competition with other critical biological functions, and long-term physiological costs.

4 Antimasking in the Auditory System

Last, but not least, are those mechanisms within the auditory chain itself that contribute to reducing masking. Many authors have noted the fact that conspecific noise is likely to have been a long and consistent factor in the evolution of antimasking adaptations (e.g., Fay and Popper 2000). In a brief overview like this, it is not possible to thoroughly treat the background literature on such well-known phenomena as a temporal release from masking by intermittent maskers or a spatial release from masking. The latter feature, in particular, has been shown to offer a considerable release from masking, enabling detection of signals that are about 12 dB below the level of the masker (Turnbull 1994; Holt and Schusterman 2007; Jones and Litovsky 2011). This is a particularly important point for modeling the masking effect of nondirectional ambient sound on a signal of interest where the receiver can, and likely does, orient to the signal of interest to optimize signal reception and processing. It is also important for reducing the masking of a signal in the presence of a point source of masking noise that is displaced by as little as a few degrees in the vertical or horizontal plane relative to the signal of interest. This important difference between masking by nondirectional ambient noise and discrete noise sources is often overlooked in discussions of the environmental consequences of man-made noise where chronic increases to ambient noise are interchanged with discussions or graphic representations of discrete and sometimes intermittent sources such as air guns, pile-driving noise, or sonars.

Recently, Branstetter and Finneran (2008) at the Navy Marine Mammal Laboratory in San Diego, CA, conducted investigations of the comodulation masking release (CMR). Their results showed a reduction in masking of up to 17 dB when the noise is coherently modulated over time, as is the case for many masking sounds where signal reverberation, differential propagation of different frequencies, and other environmental features tend to cause the received sounds to be comodulated. Their results help explain the considerable and unanticipated demasking of more than 30 dB that Erbe (2000) obtained from both a trained beluga whale and from human listeners during playbacks of a beluga whale vocalization in the presence of icebreaker, air-bubbler, and ice-cracking noise (Erbe 2000), although Erbe also noted that some frequency components of the complex test signals may also have exceeded the energy in that band of the noise spectrum, allowing the subject to reconstruct enough of the signal to correctly detect/classify it as the signal it had been trained to detect. Furthermore, because the sounds were played back from the same speaker, the listeners did not benefit from other demasking mechanisms such as the spatial release from masking.

5 Models of Masking

The two masking models best known to this community are the models advanced by Erbe and Farmer (2000) and Clark et al. (2009). The PSM-based models offered by Erbe and Farmer (2000) and by Clark et al. (2009) are based on assumptions about noise and signal energy that are not consistent with CMR, spatial release from masking, off-frequency listening, and signal redundancy. Clark et al. (2009) impose some additional correction factors that likely overestimate masking and underestimate antimasking, like the 18-dB speech recognition masking differential over simple detection, use of a directivity index based on a user-limited time bandwidth product of the signal instead of actual mammalian binaural hearing data, and assumptions that the noise envelope is of longer duration than the signal. Taking into account CMR effects of as much as 17 dB, the presence of signal harmonics in frequency bands with less masking noise and signal detection/classification at more realistic levels of 6–12 dB above PSM detection thresholds, the modelled acoustic footprint for a sound source and associated communication space reduction in Clark et al. (2009) are thus likely to overestimate masking by about 20–30 dB for a nondirectional ambient noise and more than 30 dB for a point source of noise (moving ships) where spatial release from masking would provide an additional 3–12 dB of auditory system gain. The consequent translations into spatial expressions of masking like "acoustic footprint" for a noise source or a reduction in "communication space" for a receiver are therefore quite likely overestimated by Clark et al. (2009) by 100- to 1,000-fold (the corresponding change in signal detection/classification range resulting from imposing a 20- to 30-dB increase in signal detection threshold).

Individual-based models of sound exposure like the acoustic integration model (AIM) used by Clark (described in Ellison et al. 1999; Frankel et al. 2002) or the effects of sound on the marine environment (ESME) model (Gisiner et al. 2006; Mountain 2013) offer the opportunity to endow the animat (the simulated animal navigating a simulated sound field in four dimensions), with appropriate antimasking auditory and behavioral capabilities. The animat behavioral model operating within the ESME model, the marine mammal movement and behavior (3MB) model developed by Houser (2006), is capable of capturing many, if not all, of the demasking phenomena described in this paper in a realistic, time, and space dynamic modeling process. A modified PSM model could conceivably be further modified with additional probabilistic correction factors for masking features not yet incorporated into the Clark et al. (2009) PSM model (as, for example, the probabilistic expression of the signal gain above detection required for signal identification). But the ESME model and, in particular, the 3MB submodel for animat behavior, allows for features to covary and obey nonnormal statistical distributions more readily than the PSM-based model. Whether a complex and computationally intensive model such as a highly modified PSM or a complex individual-based model is suitable for regulatory application is another question, although the US Navy uses a very similar model, the Navy acoustic effects model (NAEMO), to calculate its estimated regulatory "takes" under the Marine Mammal Protection Act (Department of the Navy 2012).

6 Expressing Risk from Masking

Given the fact that masking is a complex phenomenon, it is not surprising that political opinions and regulatory expressions of biological risk due to masking tend to vary widely. The difficulties of assessing risk from masking may account for its infrequent use as a regulatory metric despite the ubiquity and clear potential for biologically significant consequences. A basis for better understanding of the likely risk from modeled estimates of masking may emerge from the use of a modeling framework developed for the effects of underwater sound in general, the population consequences of acoustic disturbance (PCAD) model (National Research Council 2005). The model is currently being explored for several data-rich species and/or species of special concern (elephant seals, bottlenose dolphins, right whales, and beaked whales) under Office of Naval Research sponsorship (Mike Weise personal communication). The PCAD model offers a structure to quantitatively and systematically explore the metrics of stress, energy budgets, or other "currencies" to model the consequential effects on vital rates and thus on the predicted population dynamics and trends.

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Chapter 43
"Large" Tank Acoustics: How Big Is Big Enough?

Michael D. Gray, Peter H. Rogers, Arthur N. Popper, Anthony D. Hawkins, and Richard R. Fay

Abstract In this paper, we discuss the issues encountered when trying to perform hearing experiments in water-filled tanks that are several meters in lateral extent, typically large in terms of the size of the animals under study but not necessarily so with respect to the wavelengths of interest. This paper presents measurements of pressure and particle motion fields in these "large" tanks. The observed characteristics and complexities are discussed in reference to their potential impact on the planning and interpretation of hearing experiments.

Keywords Acoustic pressure • Particle velocity • Hearing

1 Introduction

Underwater hearing experiments have been conducted within water volumes varying in extent from small "tabletop" tanks (Fay and Passow 1982; Anderson and Mann 2011) to essentially semi-infinite water bodies (Chapman and Hawkins 1973; Halvorsen et al. 2012). Some of the complexities of the sound fields in the former were addressed by Parvulescu (1967) and are further investigated in a companion

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paper (see Chapter 115 by Rogers et al. In contrast, experiments performed in open water allow the establishment of relatively simple, well-controlled sound fields (Schuijf and Buwalda 1975; Hawkins 2014). In the present paper, we consider a somewhat intermediate-size set of environments consisting of tanks several meters in lateral extent, integrated with a larger substrate (floor over ground). Although such "large" tanks may appear to provide a satisfactory acoustic environment for hearing research, many of the small-tank issues described by Parvulescu (1967) persist in water tanks whose volumes are orders of magnitude larger even when their walls are made of steel or several centimeters of concrete. In these large tanks, the acoustic fields initiated by simple sources are transformed by boundary interactions so that they vary rapidly as a function of both space and frequency. The resulting fields may be difficult to model or even characterize and may not correspond well to those encountered by the studied animal in its natural environment. These issues are examined through analysis of acoustic pressure and particle velocity maps measured for several large tanks.

2 Materials and Methods

Acoustic pressure and particle motion fields were measured inside water tanks used for fish hearing experiments at two separate facilities. At the Bodega Marine Laboratory (BML), Bodega Bay, CA, a cylindrical concrete-walled tank was characterized in support of midshipman (*Porichthys notatus*) phonotaxic response studies (Zeddies et al. 2012). The tank measured 4.0 m in diameter and was filled to a water height of 0.5 m. The tank was set in a concrete base that was in direct contact with the underlying ground. Details of the foundation construction are not known. Sound was introduced at the center of the tank with an electrodynamic source (Lubell Labs AQ339) emitting a nominally axisymmetric field in the horizontal plane. The acoustic field in the horizontal plane 1.5 cm above the source center was mapped using a pair of hydrophones (Bruel & Kjær 8103) adjoining a triaxial accelerometer (PCB W356A12) made neutrally buoyant by encapsulation in syntactic foam. Experiments were run between 70 and 120 Hz, for which the radius (a) and water depth (h) were much smaller than an acoustic wavelength.

At the Tuna Research and Conservation Center (TRCC), Monterey, CA, a cylindrical steel-walled pool was characterized in support of hearing studies of continuously swimming bluefin tuna (*Thunnus orientalis*; Popper et al. 2013). The 9.14-m-diameter, 1.67-m-deep tank was recessed 0.78 m below the surface of the concrete floor of the facility. Sound was provided by a 0.61-m-diameter ring of piezoelectric line sources (ITC 6135C) at the bottom center of the tank. The sources were driven uniformly with the objective of creating an axisymmetric sound field. The acoustic field was measured in radial-vertical planes at several azimuth angles to quantify the degree of circumferential uniformity. Pressure and particle acceleration measurements were made using a capped cylinder hydrophone (ITC 6166) and two single-axis neutrally buoyant accelerometers (EDO 51585-4) oriented in the radial and vertical directions. Experiments were run between 325 and 800 Hz with the tank diameter greater than 2 acoustic wavelengths and the water depth greater than one-fourth of a wavelength. The different acoustic sizes of the TRCC and BML tanks were critical to the establishment of the disparate sound fields measured therein.

In all measurements at the BML and TRCC, sensors were suspended from an in-air structure that facilitated spatial scans. Care was taken to ensure mechanical isolation of the scanning apparatus from the tank walls and surrounding floor.

3 Results and Discussion

3.1 BML Tank

A simple model of the propagation of sound in the BML tank ignores the side walls and considers the floor of the tank to be rigid, allowing propagation to be described in terms of discrete duct modes (see, for example, Pierce 1989). When the water depth is less than one-fourth of a wavelength, propagation is said to be “cut off,” leading to a pressure field that decreases exponentially with increasing distance from the source and has a spatially invariant phase. Figure 43.1 shows the measured pressure and radial particle velocities at 95 Hz, with the latter scaled by the characteristic impedance of water (ρc). The high rate of spatial decay of both pressure and

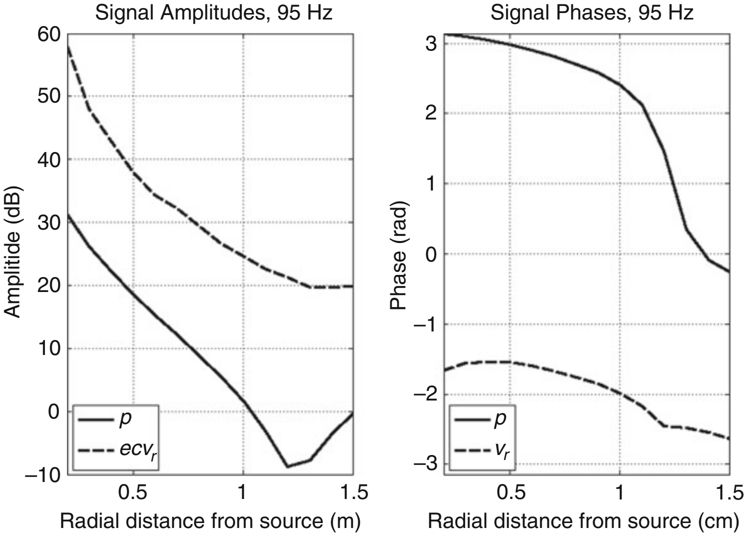

Fig. 43.1 Pressure and radial particle velocity as a function of radial distance from the source in the Bodega Marine Laboratory (Bodega Bay, CA) tank at 95 Hz. *Left*: magnitude; *right*: phase. The tank wall was 1.90 m from the source/tank center

particle velocities within 1 m of the source, the higher the decay rate of particle velocity at short ranges, and the very high absolute radial particle velocity levels (p/v_r is a complex number much smaller than ρc) are all consistent with expectations for a simple source in a rigid bottom duct. However, the measurements differ from the idealized conditions in several ways. First, the pressure and particle velocities both have a spatially varying phase. This suggests that the bottom is not acoustically rigid, and the impedance seen by the water was therefore determined by subbottom materials extending several meters below. Second, the pressure shows a local minimum near 120 cm, accompanied by a rapid phase change. This is thought to be an artifact of tank wall vibration (rather than reflection), although it is possible that the bottom composition could also produce such an effect. In either case, prediction of these effects is challenging when the properties of the structure are not known. In separate measurements, transmissions from the in-water source were found to induce significant motion in the walls of the tank (~10-cm-thick concrete), and clear sound pressure signals were observable when a hydrophone was placed on the concrete pad several meters outside the tank.

3.2 TRCC Tank

In contrast to the previous case, the TRCC tank was used in a frequency range where propagation would not be “cut off” on the basis of a rigid-bottom waveguide model. In this case, the lateral boundaries of the tank were expected to heavily influence the acoustic fields. Figure 43.2 shows pressure with overlaid particle velocity

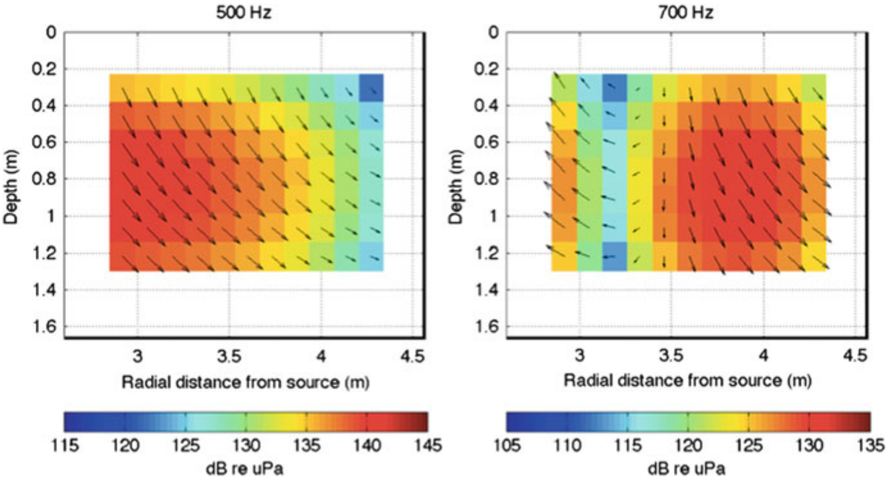

Fig. 43.2 Pressure and particle velocity vector overlays in the radial-vertical plane in the Tuna Research and Conservation Center (Monterey, CA) tank at 500 (*left*) and 700 (*right*) Hz. The tank wall was 4.57 m from the source/tank center. The water depth was 1.67 m

vectors (at a single instant of time) measured in the radial-vertical plane at a single azimuth angle. The measurement region corresponded to that through which the fish typically swam. At 500 Hz, the field was fairly simple, with the particle motion vectors pointing in a common direction and the pressure field dropping off near the wall. At 700 Hz, the field was considerably more complex, with the local minimum pressure occurring well away from the wall and particle motion vectors rotating around the pressure null. This set of conditions is particular to a water tank with well-defined lateral boundaries, with propagation determined by radial modes and exhibiting neither geometric nor exponentially decaying behaviors. The complexity of the 700-Hz data also highlights the need for the characterization of fields at a spatial resolution finer than one-half of a wavelength. In the present case, the sampling was done at approximately one-fifteenth of a wavelength at 700 Hz. As a final note on this dataset, testing conducted at lower frequencies indicated that there was only weakly pronounced “cutoff” behavior. The coupling of sound from the tank through the bottom to the surrounding substructure was evident in sound field measurements made with a single source, which showed strong circumferential asymmetry. The subsequent use of a ring source helped reinforce sound field symmetry.

4 Conclusions and Recommendations

Returning to the question posed by the title of this paper, the data presented above illustrate that consideration of only tank gross geometry and acoustic size can be misleading. The BML tank, where the dimensions were all acoustically small, provided an adequate laboratory approximation to the extremely shallow-water environments where midshipman fish nest. During hearing tests, the fish were exposed to sound within 1 m of the source, a range for which the field variables exhibited simple ductlike propagation characteristics. The TRCC tank, which was used in a frequency range where the lateral extent (diameter) was at least two wavelengths, created a complex acoustic environment with no obvious natural analog for the pelagic tuna. For tuna hearing tests, the fish were exposed to sound near the tank wall, where they preferred to swim and could safely do so at a typical continuous speed of 2 m/s. Control of the observed radial sound field complexities was not attempted, but the fine-scale spatial field scans were useful for interpreting the hearing test results.

Because it typically is not possible to find ideal laboratory conditions for conducting hearing experiments, especially for pelagic fishes, we offer the following recommendations.

1. Do not assume that “larger” tanks, such as those described in the present paper, are appropriate surrogates for open-water environments or are any more well suited to addressing a particular hearing test objective than benchtop aquariums. Sound interaction with tank boundaries may make simple or otherwise desired in-water acoustic conditions difficult to achieve or limit the spectral and spatial ranges over which they could be achieved.

2. Tank wall thickness is largely irrelevant. Do not presume that the mechanical boundaries of the tanks define the acoustic boundary conditions. Excluding resonant elastic effects, tank walls do little more than keep the water from escaping. Walls backed by air essentially present an air (low) impedance, and walls in contact with a solid foundation/ground present a finite (nonrigid) impedance defined by the substrate materials, which are typically not known in detail.
3. When resonating, commonly because of bending vibration modes, tank walls can dominate in-water field characteristics. Numerical prediction of such effects can be difficult when the construction and materials are unknown, and it is recommended instead to measure wall vibrations of candidate pools and either avoid testing at the observed resonance frequencies or attempt to isolate the walls from the water using a layer of compliant material.
4. Broadband anechoic treatments require a thickness of at least one-fourth of a wavelength to be effective. Application in the frequency range of interest for many fish experiments may be impractical (no room left in the tank for fish, source, or water). Thin ($<<\lambda/4$) treatments advertised as "anechoic" should be viewed with skepticism. It is likely that thin coatings would, at best, decouple or dampen wall resonances rather than absorb waterborne sound.
5. Tanks that are set in a foundation can exhibit unexpected in-water field characteristics due to subfloor features extending several meters below. Drains and plumbing lines may introduce field asymmetries, especially if they contain trapped air, so it is good practice to make sure that these vessels are flooded during testing.
6. Characterize the sound field before starting hearing tests. Use fractional acoustic wavelength measurement grids so that tank acoustics may be better understood. Reflections and structural vibrations can produce fields that change rapidly in space.
7. Explicitly measure both pressure and particle motion, and check them for mutual validation by calculating particle motion from pressure gradients. This process helps root out contamination due to coupling into the scanning mechanism through a structural (rather than water) path. Because transduction mechanisms differ for typical hydrophones and motion sensors, signal contamination of mechanical origin tends to impact the sensors differently. If the pressure-derived particle motion does not agree with the directly measured particle motion, both measurements may potentially be flawed. However, if the derived and directly measured motions agree, they are more likely to both be correct. Such validation should be done using complex-valued (magnitude and phase) data.

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Chapter 44
High-Resolution Analysis of Seismic Air Gun Impulses and Their Reverberant Field as Contributors to an Acoustic Environment

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Abstract In September and October 2011, a seismic survey took place in Baffin Bay, Western Greenland, in close proximity to a marine protected area (MPA). As part of the mitigation effort, five bottom-mounted marine acoustic recording units (MARUs) collected data that were used for the purpose of measuring temporal and spectral features from each impulsive event, providing a high-resolution record of seismic reverberation persistent after the direct impulse. Results were compared with ambient-noise levels as computed after the seismic survey to evidence that as a consequence of a series of repeating seismic impulses, sustained elevated levels create the potential for masking.

Keywords Impulsive noise • Anthropogenic noise • Seismic air gun surveys • Arctic acoustic ecology

1 Introduction

Worldwide, increasing economic pressures are pushing for the exploration of fossil fuel resources; however, many of these energy reserves are in remote offshore locations like the Arctic Ocean. Among such secluded sites, Baffin Bay, Western Greenland, has attracted the interest of the oil and gas industry over the last 20 years (Whittaker and Hamann 1995; Whittaker et al. 1997). Melting Arctic ice and new prospecting technologies have enabled a more thorough geophysical exploration of the area and indicate the potential for viable exploitation of the natural reserves (Moore et al. 2012). Seismic air gun surveys, a prevalent active acoustics tool for

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mapping the ocean bottom composition using transient impulsive broadband sounds, are now habitually permeating the acoustic environment of many high-latitude regions (Greene and Richardson 1988; Hildebrand 2009; Thode et al. 2010). In September and October 2011, one such seismic survey took place in Baffin Bay, in close proximity to the Melville Bay marine protected area (MPA), raising the potential for exposing local marine mammal populations to disruptive increases in noise (Cosens and Dueck 1988; Finley et al. 1990).

It is not clearly established whether marine mammals respond to noise from impulsive repetitive sources (such as that of a seismic air gun array) in the same way that they respond to continuous noise (reviewed in Richardson et al. 1995; Southall et al. 2007). Aside from the potential direct physiological harm from exposure, concern exists for the possibility of various forms of communication masking (Clark et al. 2009) generated by both the direct air gun impulse and the resulting reverberant field (Guerra et al. 2011).

A seismic air gun array produces a high-energy impulse with rapid onset that is primarily directed downward so as to map the composition of the seafloor. During a seismic exercise, the air gun is fired at regularly spaced intervals, producing a series of impulses separated by an interimpulse period. For a single impulse, at close range to the source vessel, the initial acoustic pressure wave dominates. As the impulse propagates further away and the pressure wave interacts with refractive and reflective boundaries, frequency and temporal characteristics of that initial impulse change (Urick 1983). As a consequence, these acoustic phenomena transform the direct impulse, which causes signal attenuation and time-frequency dispersion. Ultimately, this spreads energy into the interval between the impulses, resulting in an increase noise level within each interimpulse gap. This phenomenon is referred to as reverberation.

In that context, this work aims at investigating how a series of repeating seismic impulses, such as those from an industrial-scale prospecting survey exercise, can alter the local acoustic environment beyond the transient impulse alone. With that objective, the data analysis performed for this study subdivided the interimpulse period into high-resolution time windows over which standardized sound level measurements were calculated. This study focuses on the physical measurement of seismic impulses within a zone of legal protection to marine life; thus the metric considered here is one traditionally used to characterize the properties of impulsive signals as pertinent to impact on marine mammals (Nieukirk et al. 2004; Madsen 2005; Southall et al. 2007).

2 Field Site and Data Collection

2.1 Geographical Location and Geophysical Survey

Greenland's Baffin Bay is a marginal Arctic sea, bounded on the west by Baffin Island in eastern Canada and western Greenland to the east and between latitudes 70° N and 82° N. The relatively warm waters of the Greenland current generate high biological primary productivity (Williams 1986), leading to abundant and diverse fauna including several species of odontocetes, among them the largest of the Arctic's three narwhal (*Monodon monoceros*) populations numbering more than 60,000 individuals (Laidre et al. 2004; Laidre and Heide-Jorgensen 2005) and ~21,000 belugas (*Delphinapterus leucas*). Considering the ecological importance of the northwestern section of Baffin Bay, a portion of it called Melville Bay, which is used as a breeding ground for these marine mammal species, has been designated as a MPA.

In 2010, Greenland awarded several oil and gas exploration licenses within Baffin Bay, outside the limits of the Melville Bay. From 10 September through 19 October 2011, a seismic prospecting survey was performed over a territory 120 km off the coast. The vessel trailed two Sercel Sodera G-Gun II seismic arrays of three subarrays each, which fired intermittently in intervals of ~12 s. Air gun arrays were operated using a 2,000 psi onboard compressor. Each subarray consisted of seven air guns, for a combined effective volume of 4,135 in.^{3}, with 93 parallel active transect lines, each ~50 km long, performed at the maximum array volume. As the vessel turned around between headings, the seismic arrays were shut down, providing regular periods of several hours when no active seismic events were present. GPS time-stamped source logs for the survey were provided by the vessel.

2.2 Data Collection

A marine autonomous recording unit (MARU) is a digital audio-recording system that can be programmed to record at a variety of sampling frequencies and schedules (Calupca et al. 2000). An HTI-94-SSQ hydrophone with a sensitivity of −168 dB re 1 V/μPa is mounted outside the pressure-rated sphere, and its output is linked to an amplifier with a gain of 23.5 dB and an analog-to-digital (A/D) converter with a sensitivity of 103 bits/V. Based on previous calibrations ($n=18$), the sensitivity of the MARU has been determined to be −151.2 ± 1 dB re 1 μPa between 10 and 585 Hz (Parks et al. 2009).

As part of the mandatory monitoring during exploration surveys in Baffin Bay (Mosbech et al. 2007), 5 MARUs were deployed between 9 September and 24 October 2011, for a total deployment length of 45 days. All units were programmed for continuous recording at a sampling frequency of 16 kHz, with a high-pass filter applied at 5 Hz to allow for the capture of the peak energy from the seismic vessels below 10 Hz. In this paper, we present results exclusively from a unit labeled MARU 3, which was located at a range of 40 km from the northeast corner of the three-dimensional (3-D) survey area, suspended on a bottom-mounted mooring at 170 m depth in a water column 770 m deep. This MARU was chosen because it represents a midway point between the seismic vessel tracks and the MPA.

3 Data Analysis

The goal of this effort was to measure the noise-level contribution of each individual seismic impulse to the local acoustic environment and evaluate it in relationship to baseline ambient-noise levels as measured during times when the anthropogenic source was not present. These objectives require two main software approaches, which are described in detail in Sections 3.1 and 3.2.

3.1 *Extracting Features from Seismic Impulses*

A custom-developed seismic impulse detection algorithm was applied, executed on the sound environment detection and noise analysis (SEDNA) tool (Dugan et al. 2011). This analysis tool located each seismic shot within the acoustic record and extracted significant metrics from both the direct impulse and the interimpulse period.

The algorithm starts by searching for peak energy values located around the time when the source vessel log reported a shot. The propagation time between source and receiver was considered in determining this timing. Once all such unsaturated peaks are detected and following the convention established by Madsen (2005), the energy contained in the direct impulse is bounded within the duration of 90% of its energy

$$\int_{5th}^{95th} p^2(t)\,dt \tag{44.1}$$

where the parameter $p(t)$ represents the acoustic pressure-time series.

As part of the detection stage and to quantify the dispersed acoustic energy as a function of time past the initial impulse, the interimpulse interval (~12 s) is divided into subintervals (labeled quadrants), each 2.5 s in duration. The algorithm has the capacity to extract standardized acoustic metrics, not only for the impulse but also for each quadrant as well. These metrics include peak-to-peak and peak sound pressure level (SPL) and sound exposure level (SEL) and an equivalent continuous noise level (L_{EQ}). In this paper, we present only results from the latter metric

$$L_{\mathrm{EQ}} = 10\log_{10} 1/T \int_{0}^{T} \left(\frac{p_m(t)}{p_o} \right)^2 dt \tag{44.2}$$

where $p_{\mathrm{m}}(t)$ is the measured acoustic pressure-time series and p_{o} is the reference pressure, which underwater is taken as 1 μPa. The variable T represents the time window over which the sound wave pressure is integrated. L_{EQ} was deemed the most appropriate metric to use for this comparative analysis because it normalizes the noise level by that temporal window of integration (T). This becomes fitting considering that the direct impulse is evaluated over a window of variable duration as determined by (44.1), whereas the quadrants do so over a predefined T of 2.5 s.

This procedure is repeated throughout the 45-day acoustic time series, detecting each seismic impulse event and extracting its corresponding L_{EQ} and that of its subsequent quadrants. Overall, a total of over 160,000 air gun shots were detected on MARU 3.

3.2 Measuring Baseline Ambient-Noise Levels

The statistical percentiles (5th, 95th, and median) of a site-specific ambient-noise power spectrum baseline were computed using a custom-developed noise-analysis algorithm. This tool was applied to 4 days of data between 20 and 23 October 2011, after completion of the seismic survey. This algorithm integrates continuous 1-s snapshots of broadband data (0–8 kHz) to create an averaged L_{EQ} estimate of ambient noise. Data on wind speed and sea state during these days were considered to be representative of those conditions over the entire 45-day deployment, validating the assumption that this period can serve as a baseline level.

4 Results

After each detected seismic impulse event was partitioned into direct impulse and subsequent quadrants, L_{EQ} values were collected for all of them. Therefore, for each impulse event, a collection of evolving L_{EQ} values were produced.

Figure 44.1 illustrates L_{EQ} values measured for all unsaturated direct impulses recorded at MARU 3 as well as the L_{EQ} values for the first three quadrants that follow them: 0–2.5 s after the impulse, 2.5–5.0 s after the impulse, and 5.0–7.5 s after the impulse. This evolution shows the remnant energy that disperses from the impulse and how it affects the acoustic environment during the interpulse interval, even as late as 7.5 s after the shot. The oscillating structure of these L_{EQ} curves also evidences the influence of range and aspect on received levels; as the source vessel moves back and forth performing shooting lines; L_{EQ} values for a particular time window can increase or decrease by as much as 5–8 dB. Overall, reverberation levels for the interimpulse quadrants were ~3–6 dB below those of its corresponding direct impulse.

Figure 44.1 also presents the statistics of local ambient noise as measured in the absence of the seismic source. By looking at the seismic survey levels in comparison to that baseline, it is evident that at the ~40-km range, air guns can elevate ambient levels by over 25 dB, not just during the fraction of a second when the actual shot is fired but during interimpulse periods, even as late as 7.5 s after the direct impulse.

Figure 44.2 shows the distributions of L_{EQ} values for all direct impulses and their first three subsequent quadrants for the entire deployment. The Gaussian shape of these distributions further reflects the impact of source range as caused by the back-and-forth movement of the vessel and allows for a statistical understanding of the

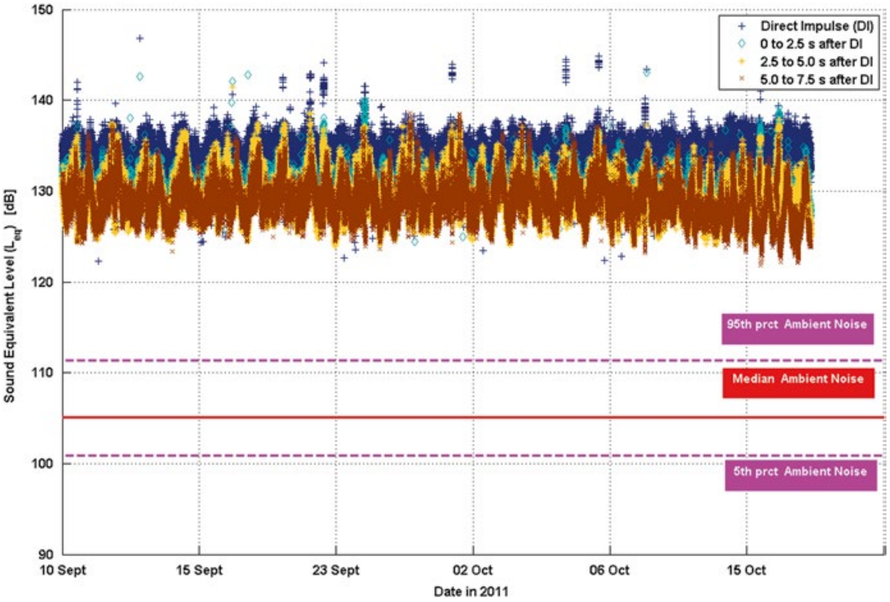

Fig. 44.1 Time series of equivalent continuous sound level (L_{EQ}) for all (nonsaturated) direct impulses and their first three subsequent quadrants (2.5 s) as measured at marine acoustic recording unit (MARU) 3 (~40-km range from source) over 45 days of seismic effort compared with ambient noise L_{EQ} values (median and 5th and 95th percentiles [prct]) as measured between 20 and 23 October 2011 at MARU 3

decay of reverberation energy in time. Notice that the distributions of the 2.5- to 5.0-s and 5.0- to 7.5-s quadrants almost perfectly overlap. One possible explanation is that contributions from other types of seismic phenomena commonly triggered by air gun surveys, such as “ground roll” or head waves, are partially responsible for raising the low-frequency background levels.

In combination, the results from Figs. 44.1 and 44.2 show that at MARU 3, levels corresponding to both the direct impulse and the periods past it were far above average ambient conditions (by as much as 25 dB). Hence, at MARU 3, at ~40 km from the source, noise levels between seismic impulses remain elevated past the direct pulse and potentially never return to the original background ambient level before the onset of a new seismic impulse.

5 Discussion

Seismic impulses were analyzed using L_{EQ} measurements over time windows that divide each seismic event into a direct impulse and three consecutive quadrants, each 2.5 s long. Because most (>90%) of the energy of an impulse is contained within the duration of that transient event, most regulatory attention has focused on

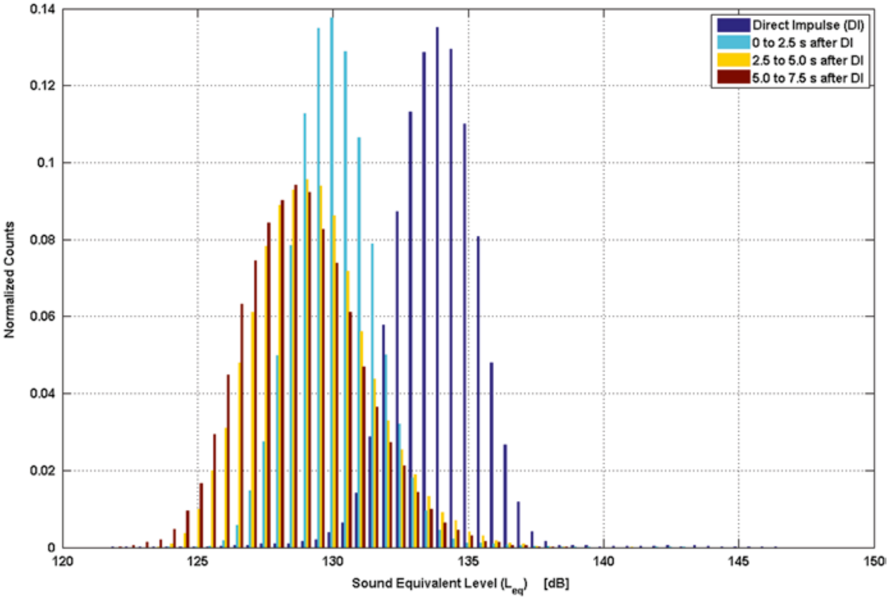

Fig. 44.2 Distribution of L_{EQ} values for all (nonsaturated) direct impulses and their first three subsequent quadrants (2.5 s) as measured at MARU 3 (~40-km range from source) over 45 days of seismic effort

reporting the potential impact of direct impulses on marine species of interest. Correspondingly, traditional metrics have emphasized the measurement of levels from the direct seismic impulse and seldom consider the influence of dispersed energy (in the form of reverberation) on the time period between impulses.

As expected, this case study confirms that the highest noise levels are reached as a result of energy from direct impulses. However, it also reveals that as a result of reverberation, measurements of noise levels during the interpulse interval can be elevated by as much as 25 dB relative to baseline ambient levels that do not have a contribution from seismic air guns. Furthermore, there was considerable variability in these measured values as a function of time, most likely due to vessel range and aspect, but possibly also caused by changing environmental variables such as sound speed.

Overall, mitigation strategies like passive acoustic monitoring (PAM) rely on the assumption that marine mammal vocalizations can be effectively monitored during active seismic surveys. These results demonstrate that an acoustic environment is impacted beyond the duration of a single impulse and that as a consequence of a series of repeating seismic impulses, persistent elevated levels may create the potential for both PAM and marine animals to be acoustically masked. These findings evidence the potential oversight in assessing the impacts of a seismic survey on the surrounding marine life, from metrics related to the individual air gun impulses alone instead of considering the totality of the industrial-scale operation at appropriate and ecologically significant time scales.

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Chapter 45
Underwater Sound Propagation Modeling Methods for Predicting Marine Animal Exposure

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Abstract The offshore exploration and production (E&P) industry requires comprehensive and accurate ocean acoustic models for determining the exposure of marine life to the high levels of sound used in seismic surveys and other E&P activities. This paper reviews the types of acoustic models most useful for predicting the propagation of undersea noise sources and describes current exposure models. The severe problems caused by model sensitivity to the uncertainty in the environment are highlighted to support the conclusion that it is vital that risk assessments include transmission loss estimates with statistical measures of confidence.

Keywords Propagation • Modeling methods • Exposure • Sensitivity • Uncertainty

1 Introduction

The information presented in this paper is a much condensed distillation of the research in progress by the authors who are funded by the Joint Oil & Gas Industry Programme on Sound and Marine Life. The main purpose of that research is to identify the best acoustic models for use by the exploration and production (E&P) industry to provide more accurate risk assessments for environmental noise exposure evaluations. Our research surveys 27 of the available high-fidelity acoustic models and catalogs an extensive set of modeling capabilities. High-fidelity models are those that capture the important physics of the problem. That survey will

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provide the most current comprehensive review of available high-fidelity acoustic models of which we are aware. Our study has also identified over 200 databases for marine physical parameters and marine animal data for supporting acoustic model inputs for animal exposure assessments.

The most common measures of the acoustic field that are provided by acoustic models are the sound pressure level (SPL) and the transmission loss (TL) at some range and depth. A common exposure metric is the broadband SPL (SPL_{BB}). However, in the evaluation of exposure to impulsive sounds, the sound exposure level (SEL), which measures the integrated sound energy or exposure, is often required. To provide this output metric, the acoustic model should compute the impulse response or received time series, which requires high-fidelity modeling (Siderius and Porter 2006). There are many mechanisms that modify sound as it propagates through the ocean. These mechanisms include spreading and refraction caused by the changing sound speed profile, absorption losses due to the fluid medium, volume scattering, sea surface interference, and interactions with the sea bottom. An important added complication is that the environmental descriptions will vary as a function of range and time. Due to the broad span of frequencies and differing types of sources involved in E&P activities, no single modeling approach can provide accurate predictions in all cases. Fortunately, acoustic modelers have produced a wide range of acoustic-propagation models, each to address a particular set of environmental circumstances.

2 Review of Acoustic-Propagation Models

There have been many methods devised to predict ocean propagation, which are briefly described by Etter (2008). Here we describe these methods and commensurate model classes that provide ocean propagation predictions. We can provide model developer contact information for the models mentioned below. A summary of the acoustic-propagation model classes is provided in Table 45.1, and Fig. 45.1 provides a diagrammatic overview of the general landscape of acoustic model classes, the model class frequency of applicability, and the required computational resources (e.g., memory, time). These classes are briefly described.

2.1 Classes of Solution Physics

Ray theory divides the sound field into a number of rays, each with a different launch angle and each traveling in a different part of the ocean. Each ray path is computed in steps, easily accommodating range-dependent changes in the environment. Impulse responses are easy to assemble from the travel time of each ray and beam patterns are easy to apply using the angular decomposition. Ray computations are very fast and accurate as long as the sound speed does not change very much

Table 45.1 Classes of acoustic models

Class	Advantages	Weaknesses	Regimen of applicability	Propagation models
Ray Theory	Fast, visual, range dependent	No rays into sediments and no diffraction	High frequency or deep water, range dependent	BELLHOP, GRAB, MOCASSIN, SPADES, TRACEO, WAVEQ3D
Parabolic Equation	Valid in strong range dependence	Extra processing for beam patterns or time series	Low frequency, ducted or deep water, range dependent	MMPE, PECAN, RAM
Normal Modes	Good for complex sediments	Accurate range dependence is very slow, many have no near field	Low frequency, shallow water, layered sediments	COUPLE, C-SNAP, KRAKEN, ORCA, POPP/PROLOS, WKBZ
Energy Flux	Fast, physically insightful	Only valid for simple cases	Broadband average intensity	INSIGHT, NUCLEUS (for marine exposure)
Wavenumber Integration	Accurate	Very slow	Low-frequency layered sediments	OASES
Finite Element/ Finite Difference.	Accurate for seismology	Requires detailed input	Low-frequency scattering and reverberation	NUCLEUS (for seismic)
Hybrid	Combines advantages of different classes	Too new to be proven yet	Presumed same as constituent classes	CMPE, RMPE

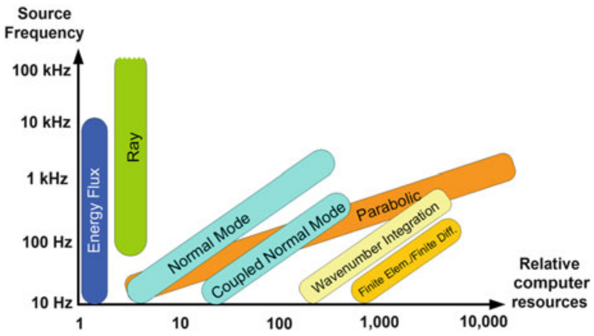

Fig. 45.1 Diagram of acoustic model classes and their relative resource requirements with increasing frequency. *Elem.* element; *Diff.* difference

over the course of a wavelength. This limits these models to high-frequency/deepwater applications. As a rule of thumb (Jensen et al. 2011), "deep water" means substantially deeper than a wavelength by a factor of 10–20. As rays reflect from the bottom boundary, propagation into the sediment is not included. Conventional ray theory predicts an infinite pressure at caustics where rays cross. Gaussian ray bundle models (CASS/GRAB, SPADES, and WAVEQ3D) and Gaussian beam models (BELLHOP and TRACEO) avoid these infinities by broadening the width of the ray using a spatial Gaussian function. MOCASSIN is a random ray model that traces rays from a distribution of angles at each boundary reflection.

Parabolic equation (PE) models solve an approximation to the wave equation that is only valid for the out-going sound field, but this solution automatically handles range dependence. Various numerical techniques can be used to solve this equation, leading to a host of PE models. Three of the best known are MMPE, PECAN, and RAM. One disadvantage of PE solutions is that the sound field is not divided in angle or time. This means that producing an impulse response is time consuming, requiring additional transforms over frequency, and applying beam patterns also requires additional processing.

Normal mode theory divides the wave equation into two independent functions, one in depth and one in range. The depth functions describe the sound in terms of standing waves between the surface and the bottom. The range functions describe a decaying sine wave with range. The product of these functions produces the sound field in range and depth. The advantages of normal mode theory are that complicated layered water and sediments are easily modeled, including shear-wave propagation and sediment surface waves. The theory provides a clear physics-based interpretation for phenomena-like shadow zone penetration, duct leakage, and tunneling. The sound field can be divided by the angle of arrival and by time, using the velocity of each mode, so that source beam patterns and impulse responses can be modeled. This theory is very useful for shallow-water and low-frequency propagation where the number of modes is small and ray theory is inaccurate.

The disadvantage of normal mode theory is that range dependence is hard to model. The exact solution requires mode coupling where energy is passed from one mode to the next as it propagates into a changing environment. This coupling, included in the models COUPLE, C-SNAP and KRAKEN, is computationally intensive, and the calculation is often only used for benchmarking other approximate techniques. One commonly used approximate technique is called adiabatic range dependence. This approximation is only valid for very small range changes, such as 1–2° bottom slopes. Adiabatic models include POPP/PROLOS, PROSIM, and WKBZ. The ORCA model has no range dependence.

Wave number integration is a term referring to techniques to numerically solve the wave equation. Time-series solutions are obtained by evaluating the wave number integrals at a number of different frequencies and then using an inverse Fourier transform. The advantage of this technique is that arbitrary layer properties, including elastic sediments, can be easily handled and a time-domain solution is obtained. These solutions are particularly well suited and efficient for short-range time-domain problems where bottom interaction is important. A major limitation of wave number integration solutions is their complexity. They are research-oriented models that require the user to have a significant understanding of the physics of wave propagation and the mathematics involved in numerical integrations. The most famous of these models is OASES (formerly SAFARI).

Finite-difference/finite-element techniques are capable of numerically solving the two-way wave equation in inhomogeneous fluid-elastic environments with complex geometry. These models are primarily used to study low- and medium-frequency scattering and reverberation from the ocean boundaries in seismology. There are three main techniques, all based on some form of direct discretization of the governing equations: finite difference, finite element, and boundary element. These types of models are all computationally intensive and require expert users and highly detailed input. They are rarely used for general ocean acoustic-propagation problems except for providing benchmark solutions. The model NUCLEUS is an example of a finite-difference technique and it is used for a wide range of applications in seismic exploration.

Energy flux models are based on the understanding that simple closed-form solutions for range-averaged or frequency-averaged transmission loss can provide a reasonably accurate description without taking explicit account of the discrete nature of propagation paths, as done in ray or mode theory. Flux methods, such as those in the model INSIGHT, seek to provide an average of the field for applications that do not need high fidelity. The solutions are quite easily found, and with a broadband source, these formulas explain the trends quite well; however, time-series representations are not given.

Hybrid models are an approach to obtaining a more universal solution to acoustic propagation over a wide range of frequencies and environments by combining several solution techniques. The idea is that one model repairs the shortcomings of the other. Despite finding several published ideas in our survey, most of them are not formalized into functional acoustic models. Two recently created models that deserve mention are CMPE and RMPE. CMPE uses a PE approach in a radial direction and normal modes in the depth direction. RMPE is a ray-mode parabolic hybrid model using normal modes in the vertical direction and mode coefficients in the horizontal direction that are found by using a PE method. The fact that there are not more hybrid models may indicate that the technique is not generally successful or requires further development to gain wider use and acceptance.

2.2 Important Factors for Marine Exposure Predictions

The frequency range of a class of models describes where they are considered valid or computationally fast enough to be employed. Because the frequencies of E&P activities span many decades, primarily from 10 Hz to nearly 100 kHz, different classes of models will be required to cover the entire scope. High-frequency models are usually ray models that are fast and efficient. Low-frequency models are usually normal mode or PE models for which run time and memory storage requirements are the limiting factors, not the physics.

Broadband is the term used to refer to the generation of propagation loss with many discrete frequencies. Many frequencies are needed to adequately sample the bandwidth of the source to compute $\mathrm{SPL}_{\mathrm{BB}}$ or to perform time-series modeling. Typically, underwater propagation models have been mathematically derived for a narrowband (single-frequency) continuous wave source. To model the propagation of short (high-bandwidth) pulses, the bandwidth of the pulse is divided into subbands. Each subband is characterized by a center frequency, and the model is run repeatedly for each subband and then summed. The presence of a sound speed duct will distort the subbands whose frequencies can be trapped there, affecting the received pulse shape.

The temporal modeling of pulse propagation in time requires calculating the dispersive character of the environment (time spreading). Considering only a single-source frequency, each propagation path or mode in the ocean will have a different arrival time. This causes the original transmitted signal to be spread in time at the receiver. Calculation of the SEL requires knowledge of this time spread.

Spatial coverage refers to the volume of the ocean that a model encompasses. The term 2-D refers to a single slice in range and depth; $N \times 2$-D refers to N independent slices, each at a different bearing; and 3-D contains true azimuthal coupling between bearings. Because the azimuthal coupling is very low, the $N \times 2$-D approach appears reasonable. Given the wide variety of sources of noise from E&P activity, incorporation of source directivity is required for determining spatial coverage.

Range dependence is a particularly important aspect of acoustic modeling. All of the environmental descriptors (e.g., sound speed, bathymetry, bottom composition, surface sea state) exhibit variability at range scales far shorter than the desired range of propagation prediction. Thus, it is vital that an acoustic model adapt the propagated pressure wave to the changing environment as it evolves outward and back.

2.3 Environmental Descriptions

All core acoustic-propagation models require the same basic description of the environment as input. This includes the water column properties (sound speed profile or temperature and salinity profiles), the bathymetry, the bottom composition or bottom reflection coefficient, and the sea surface state or surface reflection coefficient. We have catalogued a myriad of databases, largely available on the Web, that cover these input parameters. Temperature and salinity profile data at a high vertical resolution (~1 m) are available globally in the top 2,000 m of ocean. Likewise, bathymetric and sedimentary geophysical data (density, grain size distribution, sediment thickness) are globally available. However, the horizontal sampling intervals of all these data types depend highly on the marine region of interest and its survey history. Some regions are highly sampled (exclusive economic zones, in particular), whereas others are coarsely sampled and there are some regions where data are nonexistent. Sedimentary geoacoustic data (compressional and shear sound speeds, attenuation) are much more difficult to obtain in open sources; therefore, these parameters are usually calculated using available geophysical data.

3 Accuracy, Sensitivity, Uncertainty

Accuracy is very important but it is difficult to assess. Of prime importance is that models capture the dominant physics in the problem without introducing numerical artifacts to best represent what is observed in the ocean. Accuracy is measured by model-to-model comparisons and model-to-data comparisons. In model-to-model comparisons, when two different classes or techniques agree, then the conclusion is that they are both capturing the true physics of the problem, particularly if one model is regarded as a benchmark. Model-to-data comparisons are less frequent because with the complexity and time-varying nature of the ocean environment, it is very hard to compile a complete environmental description that high-fidelity models require. Furthermore, acquiring data at sea is costly. Comparisons are also difficult because a small change in a sound speed or source depth can cause major structures or focus points of the acoustic field to shift in range and depth. As a result, the numerical difference in sound level will be large and misleading. The consensus of the acoustic modelers is that all the high-fidelity models, when used within their regions of applicability and given correct inputs, are capable of accurately computing the sound field.

Sensitivity is an important factor in propagation. Acoustic sound waves propagating in the real ocean are very dependent on and sensitive to the environment. Why does sensitivity matter? It matters because small fluctuations in the environmental properties can have a major impact on the direction and strength of the wave. A high-fidelity propagation model automatically shows the same sensitivities, meaning small changes in the inputs can dramatically change the model predictions. This high sensitivity is not a failure of the acoustic model; it is a fact of propagation

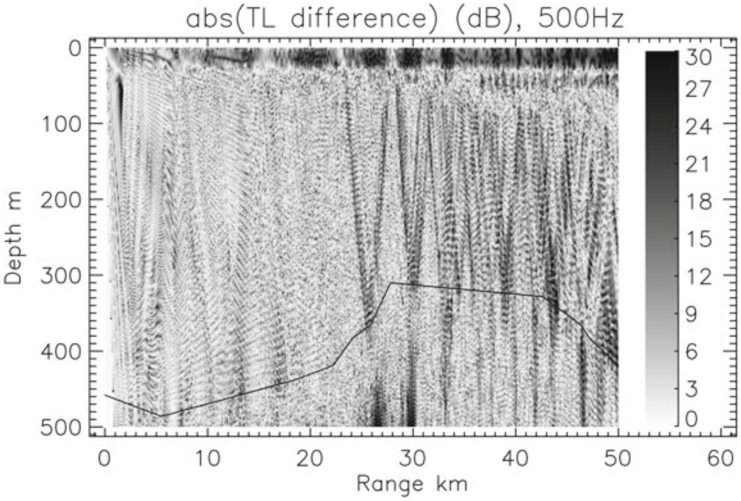

Fig. 45.2 Transmission loss (TL) differences, absolute (abs) value of ($TL_{duct} - TL_{no\ duct}$), over range and depth for a 1.5 °C increase in the surface temperature, source at 20 m, frequency 500 Hz

in the real ocean. Unfortunately, over the vastness of the ocean with the lack of timely and detailed environmental descriptions, models cannot hope to reproduce the field as it exists.

An example of sensitivity to sound speed is the "afternoon effect" discovered shortly before World War II (Urick 1983). In this case, afternoon heating of the ocean surface causes a loss of the surface duct, which greatly impacts the shape and strength of the acoustic field. Figure 45.2 displays the large differences in TL caused by a 1.5 °C increase in surface temperature that removed the duct.

Methods must be found to account for all variations in the environment to which sound propagation is highly sensitive or, equivalently, the variations in input parameters to which the acoustic model is highly sensitive. The reality is that for practical prediction purposes in real ocean environments using high-fidelity models, the high sensitivity must be quantified in the face of the unknown.

Uncertainty is the bane of acoustic modeling. Propagation loss estimates are often unreliable, not through any inherent weakness in the models but because the real ocean environment is so poorly known. Bathymetric measurements and bottom sediments are often coarsely sampled; riverine runoff, local currents, oceanic fronts, and weather conditions constantly in flux alter the stratification. It follows that when estimating potential impacts to marine animals over large areas, the sensitivity of the models virtually guarantees that the predictions will be inaccurate. Monte Carlo simulation is the most common statistical approach to coping with uncertainty in acoustic modeling (Etter 2008). There are other methods of estimating the effects of uncertainty that are currently in research; these include transport theory, closed-form intensity derivatives, ray chaos, and adjoint modeling and principal component analysis.

4 Current Exposure Application Models

Exposure application models are those that usually contain several propagation models for the core predictions. These application models then formulate the output to address a specific need such as the various metrics used for exposure predictions. Current exposure application models include AIM, ESME, INSPIRE, NAEMO, MOCASSIN, MONM, NUCLEUS, QUONOPS, and SIMPLE. Most are using similar high-fidelity core models from the classes of ray theory (BELLHOP, CASS/GRAB), PE (RAM), and normal modes (KRACKEN), with careful attention to switching classes to suit their regions of applicability.

The main differences between these exposure application models are their availability, their computer resource requirements, and their treatment of the behavior of marine animals.

5 Future Directions for Exposure Models

Our study comprises the broadest and most in-depth catalog and review of high-fidelity acoustic models that currently exists. It indicates that present exposure models employ some of the best high-fidelity models to provide the received SELs. We have summarized the techniques used by these models. One aim of our research is to highlight areas in which the models or exposure-level techniques could be improved on. It was shown by example that acoustic predictions are very sensitive to the environmental inputs used and that these inputs are prone to uncertainty or poor sampling. Therefore, it is vital that statistical measures of the spreads of the exposure levels are provided. We assert that efficient ways must be found to determine a statistical characterization of the SELs to provide a more accurate basis for acoustic risk assessments.

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Chapter 46

Investigating the Effect of Tones and Frequency Sweeps on the Collective Behavior of Penned Herring (*Clupea harengus*)

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Abstract We experimentally played back tones and sweeps to captive herring (*Clupea harengus*) in a net pen and measured the collective response of a large and a small group of fish using a camera, echo sounder, and multibeam sonar. The playbacks ranged in frequency from 160 to 500 Hz and 131 to 147 dB re 1 μPa in received sound pressure level. Herring behavior was scored by a team that blindly evaluated the observations. Overall, the responses were modest. Stronger reactions were observed at higher source levels, lower frequencies, and smaller school sizes, but there was no effect on signal rise time.

Keywords Collective response • Playback • Herring • Group size

1 Introduction

The response of fish to underwater sounds is relevant in the context of evaluating the effect of anthropogenic pressures on fish. There is increasing concern about the effect of noise and introduced sounds in the water (Popper and Hastings 2009; Slabbekoorn et al. 2010), and these considerations are finding their way into policy documents.

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The frequency content and sound pressure level of a sound are expected to be relevant when assessing the potential response in fish (Blaxter and Hoss 1981; Blaxter et al. 1981; Kastelein et al. 2008). In addition, the nature of the sound (e.g., information content or “abruptness”) may be important in eliciting a behavioral response. For example, herring react to killer whale vocalizations but not to military sonar, which are similar in frequency and received levels (Doksæter et al. 2009; Sivle et al. 2012). When playing back underwater sounds, Schwarz and Greer (1984) found limited reactions to natural sounds, whereas some synthesized sounds and vessel noise elicited responses.

When behavioral responses in which the reaction to stimuli involves a decision-making process (i.e., not startle responses) are addressed, several factors can determine the level and nature of the reaction. The response to a given stimulus may depend on the state of the fish (e.g., whether the fish is hungry or vigilant). This state-dependent response has been compared with the response to predation risk (Lima and Dill 1990), and the body of work on state-dependent responses to the predation risk may serve to help understand the effect of anthropogenic sound on fish behavior. A particularly interesting aspect is the collective behavior of fish. The size and internal structure of the fish school are important parameters when the response to predation-like stimuli is assessed and interpreted (Handegard et al. 2012). The response should therefore be expected to depend on the group size and structure of the fish school.

Our objective was to investigate the effect of synthesized tones on the collective behavior of herring. We were interested in the influence of the nature of the sound (e.g., sweeps vs. single frequencies); the effect of source level, frequency, and rise time of the amplitude envelope of the tones; and the effect of fish school size on behavioral reactions to underwater sound.

2 Materials and Methods

2.1 Captive Herring

In April 2012, 15 t of adult Norwegian spring-spawning herring were caught by a commercial purse-seine vessel. The fish were transported by towing them slowly with equipment designed to minimize stress over 15 h to an aquaculture facility operated by the Institute of Marine Research in Austevoll, near Bergen, Norway. After arriving at the station, the fish were kept in two adjacent rectangular net pens, 12 m long by 12 m wide by 12 m deep (volume 1,440 m^3) and fed with small-sized salmon feed. During holding, the herring were equally divided between the two pens.

During the experiments (2–13 July 2013), one pen was used as a holding pen and the other as the experimental pen. The mean length of the herring during the experiment was 31 cm and the mean weight was 211 g. Fish were transferred between the pens by creating a net tunnel and gently herding the fish into the tunnel with a seine net.

2.2 Sound Exposures and Design

The experiment consisted of 18 experimental blocks, 8 blocks of small-group size and 9 blocks of large-group size. The group sizes were not randomized due to logistical constraints, and the 8 blocks of small-group size were performed before the large group was tested. The large group consisted of all the fish, whereas the small group was significantly less, ~10% of the large group.

Within each block, 10 t and 2 sweeps were played back in random order. The pure single-frequency tones were randomly selected from frequencies of 160, 320, and 500 Hz, source levels (sound pressure levels) of 155, 165, and 175 dB re 1 μPa, and inswing times of 18, 31, and 250 ms (Fig. 46.1). The duration of each tone was 2,000 ms. A given combination was not repeated within the same block. The sweeps covered the frequency band from 160 to 500 Hz; one was an upsweep and one was a downsweep, with a fixed source level of 175 dB re 1 μPa and a duration of 5,000 ms. There was a 120-s pause between exposures within the block.

2.3 Sound Generation and Amplifier Chain

The sounds were generated using MATLAB and played through a Hegel HD2 High End USB digital-to-analog converter connected to a Cerwin-Vega CXA-10 power amplifier. The digital-to-analog converter's frequency response was modified to produce an output down to 5 Hz. The amplifier was connected to an underwater transducer with a moving-coil electromagnet design, an operating frequency of 40–7,000 Hz, and a nominal maximum source level of 200 dB re 1 μPa at 1 m placed at depths of 5 and 11 m away from the side wall of the pen.

2.4 Measuring Sound Pressure Levels Within the Pen

The sound pressure levels in the net pen were measured with a Brüel & Kjær type 8106 hydrophone placed 2.6 m away from the corner of the pen that was closest to the underwater loudspeaker, amplified, and filtered by a Brüel & Kjær Nexus conditioning amplifier. The data were digitized using a National Instruments PC-based analog-to-digital converter and calibrated using a Brüel & Kjær calibrator type 4229 with a WA 0658 coupler.

2.5 Fish Behavior Observations

A 120-kHz Simrad EK 60 scientific echo sounder was used to observe the vertical distribution of the herring school in the pen. A Simrad ES120-7D transducer was mounted on a gimbal near the center of the pen (at ~9 m depth) to ensure that the beam pointed vertically upward. A horizontally oriented DIDSON (1.1/1–8 MHz)

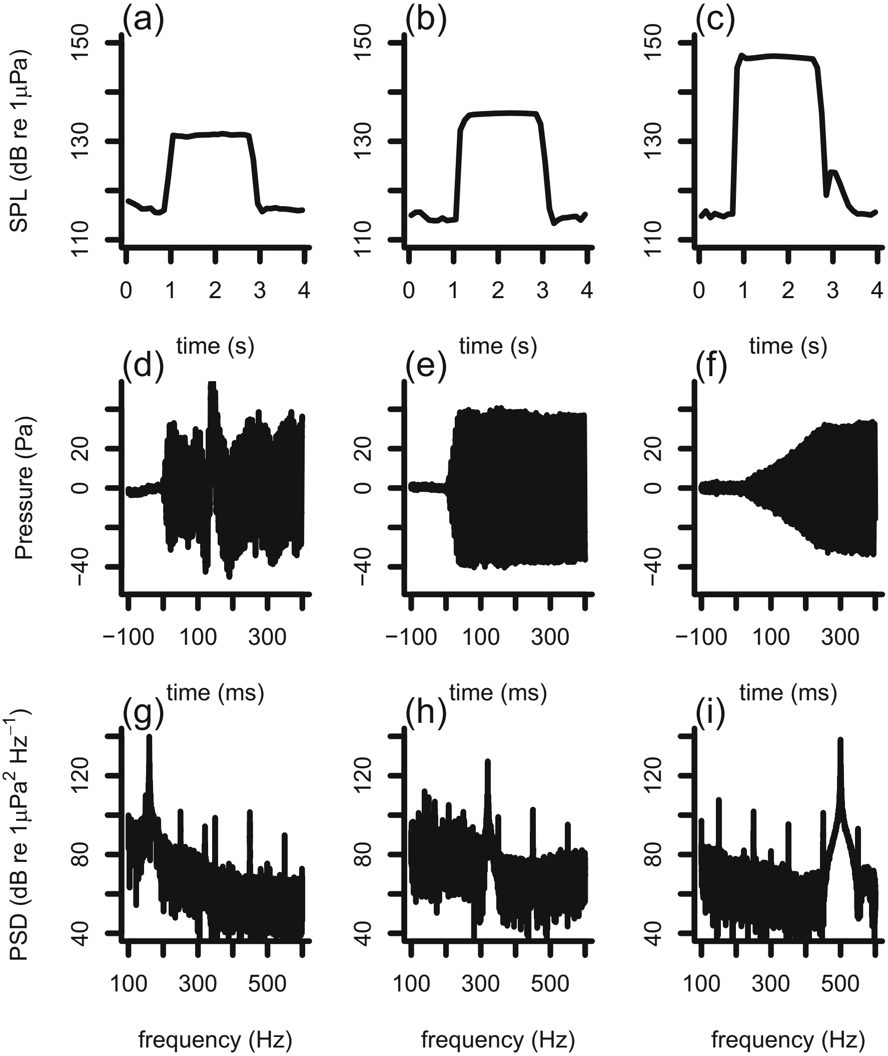

Fig. 46.1 Received sounds in the pen. (**a**–**c**) Received level for source levels of 155 (**a**), 165 (**b**), and 175 (**c**) dB re 1 μPa. Rise time was 18 ms and 160 Hz. SPL, sound pressure level. (**d**–**f**) Pressure as a function of time rise times *x* (**d**), *y* (**e**), and *z* (**f**). The source level was 175 dB re 1 μPa and frequency was 160 Hz. (**g**–**i**) Power spectral density (PSD) of the received signal for frequencies of 160 (**g**), 320 (**h**), and 500 (**i**) Hz. Rise time was 18 ms and the source level was 175 dB re 1 μPa

imaging sonar was positioned in the pen so that the center of the DIDSON beam was at 1.5 m. The DIDSON was operated in high-frequency mode (1.8 MHz) at a ping rate of 7 Hz with a window start of 1.29 m and window length of 10.28 m. The focal range was calculated to be 6.89 m. A high-resolution night view color LED camera (Sony 500TVL HQ 560TVL) was placed near the bottom, 3 m away from the pen wall.

2.6 Data Analysis

To analyze the data, we anonymized the files and used a blind scoring setup. Videos, echograms (i.e., visual representations of volume backscatter), and DIDSON videos were prepared and information related to identifying the treatments was removed (except for group size that was detectable from the images). Five analysts, without knowledge of the experimental design, scored each video and image from 0 to 5, where 5 represented a strong behavioral response and 0 no response. The mean response over the scorers (5) and observation types (3) was calculated for each treatment. The resulting response for each treatment was the mean over the 15 observations. The mean value is likely to be normally distributed, which allows for parametric statistics.

To test for a reaction/no reaction is challenging because it relies on a definition of a reaction and the scorer's abilities to assess that. This is particularly true if there is a weak response. Consequently, the estimate of the behavioral response is qualitative on a scale from 0 to 5, and the results should be interpreted with this in mind. However, the scoring is efficient when testing for relative differences (i.e., if the response is stronger to one kind of stimulus rather than another).

We used ANOVA to test for a difference in the reaction to sweeps and tones while controlling for source levels. Furthermore, we used ANOVA with the sweeps removed to test if source level, frequency, rise time, and group size affected the behavioral score.

3 Results

3.1 Received Levels in the Pen

The received levels in the pen at the position of the hydrophone were 131, 135.5, and 147 dB for source levels of 155, 165, and 175 dB re 1 µPa, respectively.

3.2 Fish Response

The mean response score was 0.51 ± 0.21 (SD), indicating a weak or nonexistent overall reaction, and any differences among treatments must be considered small because no clear response was observed overall. First, we tested if the upsweeps initiated stronger responses than pure tones while controlling for source level and group size. Note that rise time and frequency are not relevant for sweeps, and these factors were not considered in the ANOVA. The source levels ($F = 7.7$, $P = 0.007$) and group size ($F = 14$, $P < 0.001$) were significant in explaining the variance in the data, whereas the factor sweep/tone was not ($F = 1.1$, $P = 0.3$). The results show that source level and group size were important factors but that no difference was detected between pure tones and sweeps. The residuals were close to normally distributed and homoscedastic.

The second test included rise time and frequency but with the sweeps removed to test for rise times and pure-tone frequency. Again, the mean score was low (0.51±0.20), indicating a weak or nonexistent overall response. The response to source level, frequency, rise time and group size shows a weak increase in response with source level, a weak reduction with frequency, and a stronger reaction for the small group compared with the larger group (Fig. 46.2). The ANOVA shows that

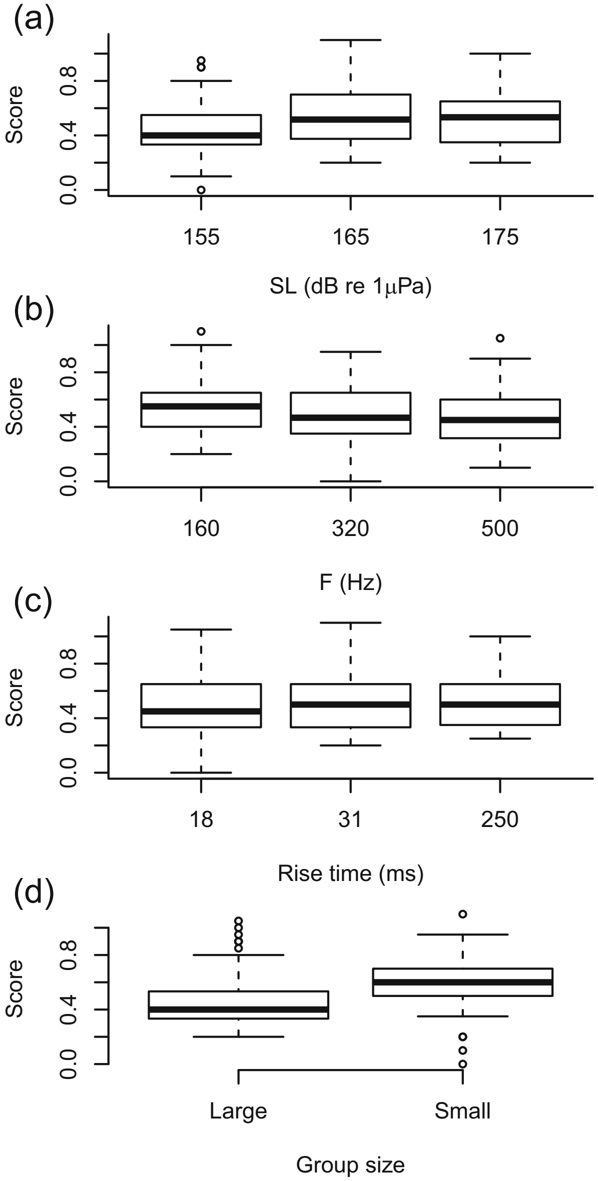

Fig. 46.2 Boxplot of the score of the different treatments explained by source level (SL; **a**), frequency (F; **b**), rise time (**c**), and group size (**d**)

source level ($F = 4.94$, $P = 0.027$), frequency ($F = 4.65$, $P = 0.032$), and group size ($F = 18.8$, $P < 0.001$) explain part of the variance, whereas rise time does not ($F = 1.26$, $P = 0.26$). The residuals were normally distributed and homoscedastic.

4 Discussion

Before the experiment, we expected that the source level and frequency content were important factors. The more interesting and novel aspects were the effect of group size and envelope steepness. These are indicators of the "nature" of the sound beyond received levels and frequency, and a response graded by the level of security of being in a dense school. The overall result is that the reaction is weak or nonexistent but that there is a stronger response to higher source levels, lower frequencies, and smaller group size. No effect was found for rise time of the amplitude envelope.

A challenge was that assessing the behavioral response is more difficult when the response is weak. We initially planned on using more automated algorithms to extract the behavioral response from the data (Doksæter et al. 2012) for examples of analyzing echo sounder data and for analyzing DIDSON data (Handegard et al. 2009, 2012), but the signal was too weak to be picked up with these methods. Instead, we chose to use a manual scoring team. The results were more qualitative and the absolute level of the reaction was hard to assess, but the difference in responses among treatments should be detectable. When the effect of group size is assessed, the results need to be interpreted with care. The video and echo sounder data appear different across group sizes, which may influence the scorer. It was not feasible to have a new, naïve group of fish for every block and this raises an issue with pseudoreplication (Hurlbert 1984). Because our objective was to assess the response in a large herring school, it was not feasible to avoid this and the results need to be interpreted with these cautions in mind.

We were particularly interested in the collective response of herring to sound stimuli because a strong collective response has been observed for herring responding to research vessels in the wild (Ona et al. 2007; Hjellvik et al. 2008). The collective behavior of herring is also a good example for collective behavior in general and complements work in this field on other species (e.g., Katz et al. 2011). In particular, it is important to understand the amplification or damping of the response due to conspecifics in the school when assessing the reaction to external stimuli.

In conclusion, the responses of herrings to the playbacks were weak, making a more detailed analysis of their response difficult, but there is an effect of source level and frequency. There is also quite likely an effect of group size, indicating that the collective mechanism is important when assessing stimuli-response behavior.

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Chapter 47
The Challenges of Analyzing Behavioral Response Study Data: An Overview of the MOCHA (Multi-study OCean Acoustics Human Effects Analysis) Project

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and Patrick J.O. Miller**

Abstract This paper describes the MOCHA project which aims to develop novel approaches for the analysis of data collected during Behavioral Response Studies (BRSs). BRSs are experiments aimed at directly quantifying the effects of controlled dosages of natural or anthropogenic stimuli (typically sound) on marine mammal behavior. These experiments typically result in low sample size, relative to variability, and so we are looking at a number of studies in combination to maximize the gain from each one. We describe a suite of analytical tools applied to BRS data on beaked whales, including a simulation study aimed at informing future experimental design.

Keywords Sonar • Cetaceans • Change-point • Dose–response • State-space modelling

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1 Introduction

Many marine mammals rely on sound for foraging, maintaining group cohesion, navigation, finding mates and avoiding predators. Hence, they may be profoundly affected by the introduction of anthropogenic noise into the marine environment. Examples of potentially harmful noise sources include vessel noise and active acoustic devices such as naval sonar or airguns used for seismic prospecting. Potential adverse effects range from masking, i.e., reducing the range at which an animal can detect important natural signals, to longer-term behavioral disturbance, which may exclude animals from important habitat, to stranding. There is, therefore, the need to quantify the impact of noise at the level of individual animal responses and also in terms of potential population consequences.

BRSs (also sometimes called controlled exposure experiments (CEEs)) are an important approach for studying the short-term responses of animals to specific doses of potential stressors. In a BRS, focal animals are selected based upon our ability to attach tags to them and their behavior monitored using visual observations, passive acoustics, animal-borne tags or a combination of these. A sample of animals is exposed to a stimulus, such as a potentially disturbing sound, and their response monitored. Various experimental protocols have been employed, including escalating the dose until a response is observed; exposing the same animal multiple times using various stimuli; varying the context of the experiment (such as the animal's behavior before the experiment or the path of the source vessel). Care is taken to ensure the experimental animals are not stressed more than is necessary for the experimental results, for example by ceasing the stimulus as soon as a response is detected. Various measurements are recorded before, during and after exposure, including location (in 3D) through time, acoustic behavior, orientation and movement recorded continuously by tags and behavior observed at the surface.

BRS experiments are extremely costly to undertake: a single field season may cost many hundreds of thousands of dollars. Many species of interest occur at low density, or are hard to monitor (for example if they are visually cryptic and difficult to tag), and experiments can only take place in good weather conditions and when other interfering noise sources are not present. Because of these factors, the sample sizes associated with BRS experiments are usually very low: typically fewer than ten exposures per species per field season, and sometimes substantially fewer. Despite the difficulties, BRSs are essential components of risk assessment because they offer a direct measure of the effect of sound on behavior from animals selected at random (in terms of their sensitivity to sonar).

1.1 Data Summary

Here we focus primarily on studies funded by the US Navy to investigate the effect of mid-frequency active sonar. The first such BRS was conducted in 2007 and 2008 in the Bahamas (Tyack et al. 2011) with the aim of collecting baseline data on animal behavior, and conducting CEEs to measure responses to different sound stimuli. A major focus of the Bahamas work was beaked whales, which are thought to be some of the species most vulnerable to sounds from sonar exercises as they make up the majority of animals stranded in association with naval sonar exercises (D'Amico et al 2009). A second project, 3S (for "Sea mammals, Sonar, Safety"), which aimed to determine behavioral responses of killer, sperm and pilot whales to different sonar frequencies, commenced in 2006 with funding from The Royal Norwegian and Dutch Navies, and in 2008 additional US-Naval support allowed a significant expansion of the effort (Miller et al 2011, 2012). Field work was conducted in Norwegian waters. A follow-up project (3S2, 2011–2013) is focusing on three different species (humpback, minke and northern bottlenose whales) and is also investigating the effectiveness of ramp-up as a mitigation strategy (Kvadsheim et al. 2011, 2012). SOCAL-BRS is a 5-year (2010–2015) study in southern Californian waters, which aims to expand on the work conducted in the Bahamas by increasing the number of species studied and by integrating with other field efforts being conducted in the same region (Southall et al. 2012). Finally, Duke University is carrying out CEEs on odontocete species off Cape Hatteras, California and Hawaii, to investigate how species-specific social structures may modulate responses to the sounds of potential predators.

All of these BRSs have relied on a suite of existing data collection technologies and methodologies that have enabled collection of a wide range of behavioral metrics. Observer-based metrics are derived from visual protocols for the collection of data on position, orientation, social configuration, surfacing behavior and swim speed of individuals and groups before, during and after a CEE (e.g., Visser et al. 2011). These data are difficult to collect for the more cryptic and deep-diving species, but animal-borne digital acoustic recording tags (DTAGs, Johnson and Tyack 2003) have proven invaluable for this purpose. These tags are attached to cetaceans using suction cups and collect acoustic and movement data for the duration of attachment. Their deployment on unexposed animals has provided valuable baseline data on diving and foraging behavior (e.g. Tyack et al. 2006), while their use during BRS experiments has allowed the behavior of exposed individuals to be tracked in fine detail before, during and after exposure. The acoustic sensor on these tags can also provide direct measurements of received sound levels.

Whilst there has been considerable consistency in the technologies employed across all the BRSs there have also been a range of important differences that need to be understood when collating and comparing data across studies. The most obvious difference is geographical location, resulting in differences in bathymetry, distance to coastline, sound propagation properties and prey availability (i.e., motivation to remain in area). In addition, the species that have been used in CEEs have differed both within and across studies. Finally the characteristics and context of each CEE differ in terms of the behavioral context of the subjects, sound types, sound frequencies, exposure durations, position/direction/movement of source relative to animal and distance from source to animal.

1.2 Analytical Challenges and the Aims of MOCHA

Many diverse analyses have been applied to data from each BRS, and we do not attempt to review them all here (although see Tyack et al. 2011; Miller et al. 2012; Curé et al. 2012; DeRuiter et al. 2013 for examples). Typically the first stage has been to synthesize the observational data for each individual to determine whether it responded, gauge the magnitude of any response and relate the onset of response to exposure intensity ("dose"). Secondly, results from individual exposures may be analyzed together to estimate a (context-specific) exposure-response function. Both stages are fraught with difficulties. At the first stage, it is not clear whether or how to combine the diverse input metrics (such as position, orientation, swim speed, dive time, social configuration and surfacing behavior) all measured through time, into a single measure of response. At both stages, analyses need to account for dependencies in the data, because many measurements are taken in close succession on the same subjects. The same subjects may also be exposed multiple times. While there are many measurements on each subject, there are few exposures in total, and often even fewer individual subject animals. In such circumstances, analysis approaches based on traditional statistical hypothesis testing and estimation have restrictive assumptions and their statistical power is often very low. This has the undesirable effect that only studies on species showing the clearest responses are likely to provide statistically significant results that are easily publishable in top academic journals, where few studies are published that show "no effect" (Dwan et al. 2008). This can lead to a potential bias in published effect levels, such that some species are thought to be more sensitive on average than is actually the case and others are assumed not to respond at all.

Despite the complications, we believe that substantial progress can be made to enhance the inferences drawn from existing and future BRS data. To this end, the MOCHA project (Multi-study OCean acoustics Human effects Analysis, running from 2012 to 2015) brings together researchers undertaking BRS studies and statisticians specializing in the analysis of biological experiments of this kind in a working group format, with dedicated researcher effort between group meetings. We are primarily working on the following four areas of research:

1. Improved methods for combining diverse behavioral measures into a response metric. Consideration is being given to obtaining metrics that can be linked to biological consequences;
2. Better estimates of exposure-response functions from individual studies through the use of cutting edge (e.g. hierarchical Bayesian) statistical techniques;
3. Combine information across studies and species ("meta-analysis"), making use of expert biological opinion, to maximize the gain for each study and to make inference about taxa and contexts not yet studied. Differences in methods/protocols between studies will need to be accounted for. A component of this objective is to quantify the similarity/dissimilarity between species, placed into functional groups.
4. Sensitivity analyses to quantify where future experimental effort will most reduce uncertainty.

Effort to date has focused on deep diving odontocetes (beaked whales and sperm whales) and other odontocete species (including killer whales, Risso's dolphins and pilot whales). Our penultimate working group meeting in early 2014 will focus on baleen whales. Reports from each working group meeting are available on the project website (http://www.creem.st-and.ac.uk/mocha/).

2 Case Study: Analysis of BRS Data from Beaked Whales

Over the course of the project a number of different methodologies have been investigated, developed and applied to a variety of BRS datasets. Here we describe a suite of analyses that have been applied to one dataset to provide examples of methods that can be applied in the context of BRSs. In both 2010 and 2011 the SOCAL BRS team successfully tagged (with DTAGs) a *Ziphius cavirostris* and carried out a CEE with mid-frequency active sonar on each animal at a distance of <10 km, with received levels ranging from 84 to 144 dB re 1 μPa root-mean-squared (rms). The whale tagged in 2011 was additionally incidentally exposed to MFA from a distant naval exercise (approximately 118 km away) with received levels of 78–106 dB re 1 μPa rms. Full details of the CEEs are given by Southall et al. (2012) and an analysis of some observed responses is given by DeRuiter et al. (2013). As is the case with all CEEs that involve tagged whales, the resulting dataset included a large number of measured and derived variables.

All the data were examined by experts and changes in behavior were identified and scored according to the Southall et al. (2007) response severity scale. Miller et al. (2012) describe this as expert scoring and outline their scoring method in detail as applied to the 3S data. The ideal scenario, however, is to use quantitative methods to identify points in time where behaviour differs from baseline ("change-points"). Here we give an example of a method that can be used to identify change-points across multivariate space (e.g., DTAG dive parameters).

Mahalanobis distance is a scale-invariant measure of distance in multi-dimensional space, which takes into account correlations between parameters. It has allowed us to summarize the multivariate time-series of dive parameters as a univariate time-series, with one value per dive. Each dive in the time-series was classified as either a deep foraging dive or a shallow dive, and the Mahalanobis distance was calculated relative to the average baseline dive of the corresponding type. The time-series of Mahalanobis distances for the two exposed *Ziphius* (Fig. 47.1) show large peaks in the distance metric around the time of the CEE exposures, corresponding to the strong avoidance response identified by expert scoring (DeRuiter et al. 2013). In contrast, the incidental naval MFA exposure did not elicit a similar response. The Mahalanobis distance was then used as a measure of response intensity and was modelled as a function of RL, source-whale range, and time since sonar exposure (DeRuiter et al. 2013) (model fit shown in Fig. 47.1); results indicated that both RL and source-whale range influenced the strength of response.

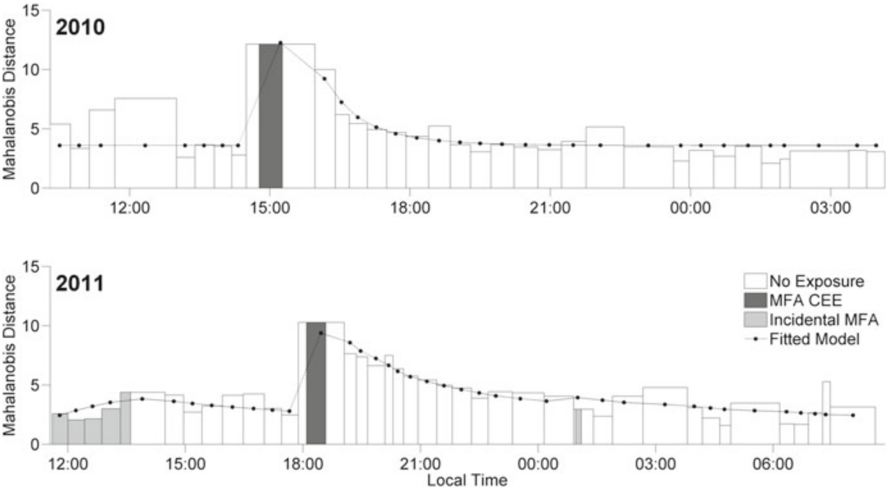

Fig. 47.1 Mahalanobis distance (modelled as response intensity) for each dive in the DTAG time-series for the 2010 and 2011 whales. Each *box* relates to one dive cycle and the area shaded in *dark grey* is the period of controlled exposure and the area shaded in *light grey* is the incidental exposure in 2011. The *dotted line* relates to the fitted model

The potentially confounding relationship between RL and range described by De Ruiter et al. (2013) posed an interesting question about experimental design. Across all BRSs the source-whale range for CEEs has been relatively low (generally less than 10 km); however, the incidental exposure that occurred at a distance of 118 km during the SOCAL BRS in 2011 suggests that response to similar RLs may differ depending on range. We therefore conducted a simulation study to investigate how many more CEEs would need to be carried out under different experimental designs to allow reliable estimation of range and RL parameters in the aforementioned response intensity model. The simulation consisted of 13 control whales and between 4 and 12 exposed whales. Three different experimental scenarios were trialled (all source levels are given in dB re 1 μPa-m): (1) source level at 210 dB and range randomly selected from 5, 10, 20, 40 or 80 km; (2) source level at 235 dB and range randomly selected as before; and (3) source level assigned as 210 dB to half of the whales and 235 dB to the other half and range randomly selected as before. Mahalanobis distances were simulated from the model described above, using the maximum likelihood parameter estimates, and then the model was fitted to the simulated data in exactly the same way as it was fitted to the observed data. We found that in scenarios 1–2, at least 6–10 exposure whales would be required to allow reliable parameter estimation, whereas varying both the source level and range (scenario 3) reduced the uncertainty considerably after only 4 whales were exposed (Fig. 47.2). Differences are also apparent between scenarios 1 and 2 whereby uncertainty is lower when source level is higher (Fig. 47.2). This difference probably arises because higher source levels generate higher received levels and more intense simulated responses, which facilitates parameter estimation.

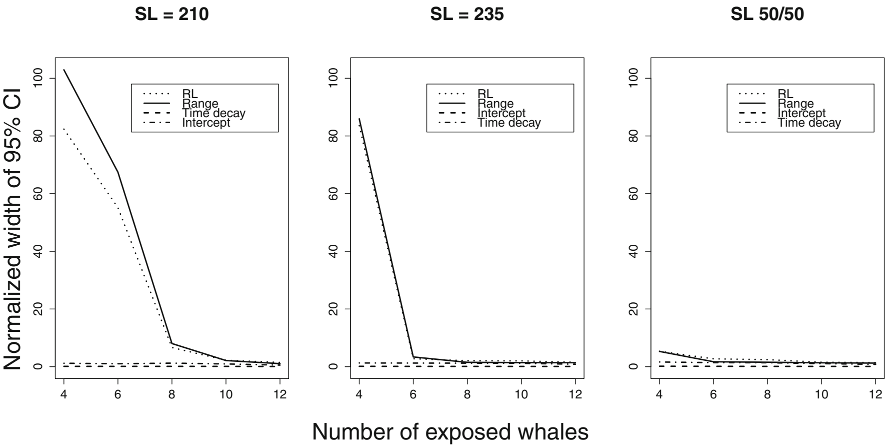

Fig. 47.2 Uncertainty expressed as the width of the 95% confidence intervals around each of the four parameters in the model, normalized by the parameter estimates. The three panels represent the three different experimental scenarios: source level 210 dB (*left panel*), source level 235 dB (*middle panel*) and source level assigned as 210 dB to half of the whales and 235 dB to the other half (*right panel*)

This result demonstrates the utility of simulation studies in exploring the potential outcomes of different experimental designs.

Finally, the scored responses for these two individuals have been combined with expert scored responses from other studies to estimate context-specific exposure-response functions. We developed and fitted a Bayesian hierarchical model to expert-scored behavioral responses and associated RLs for 35 exposure events, including four sonar signal types and 17 cetaceans of five species. We have investigated two possible approaches which help us address slightly different questions—fitting species/species groups as a fixed effect and fitting species/species groups as a random effect. When fitted as a fixed effect we can make inference about the individual species or species group, whilst fitting as a random effect allows us to make inference about unstudied species. Thus far we have been investigating the sensitivity of the methodology to different model parameterizations and the potential for model selection methods to identify species groupings, which may help with the knowledge base for legislation.

By describing this case study we have given a brief overview of a subset of the analysis methods that have been investigated by the MOCHA team to date. We outlined above the use of Mahalanobis distance as an aid to detect change-points on a dive-by-dive basis but we are also looking at its application to fine-scale time-series data. In addition we have investigated the application of a number of quantitative univariate change-point detection methods (e.g. inflection point detection, broken stick regression, wavelet analysis) to single metrics and to the time-series of Mahalanobis distances. We have also made progress in the application of process-based time series models such as hidden Markov models (HMMs) and semi-Markov models (SMMs) to BRS data. Like Mahalanobis distance, they allow multiple metrics to be combined into one analysis, and also address the time-series nature of the data, and provide an opportunity to explore behavioral states and the probability of transitioning between these states as a function of sound exposure.

3 Concluding Remarks

BRSs produce a large and complex suite of data streams, many of which could contain a signal indicating a response to sound exposure. Moreover these data relate to relatively small numbers of exposures and even smaller numbers of individuals. Therefore challenges include condensing these data into manageable and interpretable metrics for analysis, conducting analysis appropriate for small sample sizes and finally placing the results into context. The combined efforts of the individual BRS project teams and the MOCHA project are producing useful insights into a range of methods for all stages of analysis and allowing a suite of analytical tools to be developed and/or adapted for application to these data.

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Chapter 48
National Oceanic and Atmospheric Administration's Cetacean and Sound Mapping Effort: Continuing Forward with an Integrated Ocean Noise Strategy

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Abstract To help manage chronic and cumulative impacts of human activities on marine mammals, the National Oceanic and Atmospheric Administration (NOAA) convened two working groups, the Underwater Sound Field Mapping Working Group (SoundMap) and the Cetacean Density and Distribution Mapping Working Group (CetMap), with overarching effort of both groups referred to as CetSound, which (1) mapped the predicted contribution of human sound sources to ocean noise and (2) provided region/time/species-specific cetacean density and distribution maps. Mapping products were presented at a symposium where future priorities were identified, including institutionalization/integration of the CetSound effort within NOAA-wide goals and programs, creation of forums and mechanisms for

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external input and funding, and expanded outreach/education. NOAA is subsequently developing an ocean noise strategy to articulate noise conservation goals and further identify science and management actions needed to support them.

Keywords CetSound • CetMap • SoundMap • National oceanic and atmospheric administration • Ocean noise strategy

1 Introduction

In 2011, the National Oceanic and Atmospheric Administration (NOAA) convened two independent working groups to develop new methods to help better manage the chronic and cumulative impacts of human activities on marine mammals throughout the US exclusive economic zone (EEZ). The Underwater Sound Field Mapping Working Group (SoundMap) developed tools to map the contribution of human sound sources to underwater ocean noise in US waters. The Cetacean Density and Distribution Mapping Working Group (CetMap) worked to provide regional time- and species-specific cetacean density and distribution maps in US waters. Analysis teams from Heat, Light and Sound Research, Inc. (HLS), and Duke University's Marine Geospatial Ecology Lab (Duke) were contracted to assist tool-building efforts for SoundMap and CetMap, respectively. This 1-year analytical effort was financially supported by NOAA, the Navy, and the Bureau of Ocean Energy Management (BOEM).

In May 2012, near-final CetMap and SoundMap products were presented at a symposium where multistakeholder participants discussed improvement, maintenance, and growth of the products. Both SoundMap and CetMap products as well as the final report from the symposium may be accessed at http://cetsound.noaa.gov.

1.1 SoundMap

The specific objective of SoundMap was to develop and apply mapping methods to depict temporal, spatial, and spectral characteristics of underwater noise resulting from human activity. The tools developed use environmental descriptors and the distribution, density, and acoustic characteristics of human activities within US waters to depict first-order estimates of their contribution to background noise levels at multiple frequencies, depths, and spatial/temporal scales. SoundMap focused on developing feasible methods that could be implemented within a 1-year analytical effort. It was necessary to apply a variety of informed approximations to enhance computational feasibility and to bridge data gaps. All extrapolations and assumptions made in producing these products have been explicitly documented in methodology summaries and are available on the Web site with each dataset. These summaries are intended to assist users in understanding the current status of the data used for this effort, the methodologies applied, and the requirements for producing different or higher resolution products in the future.

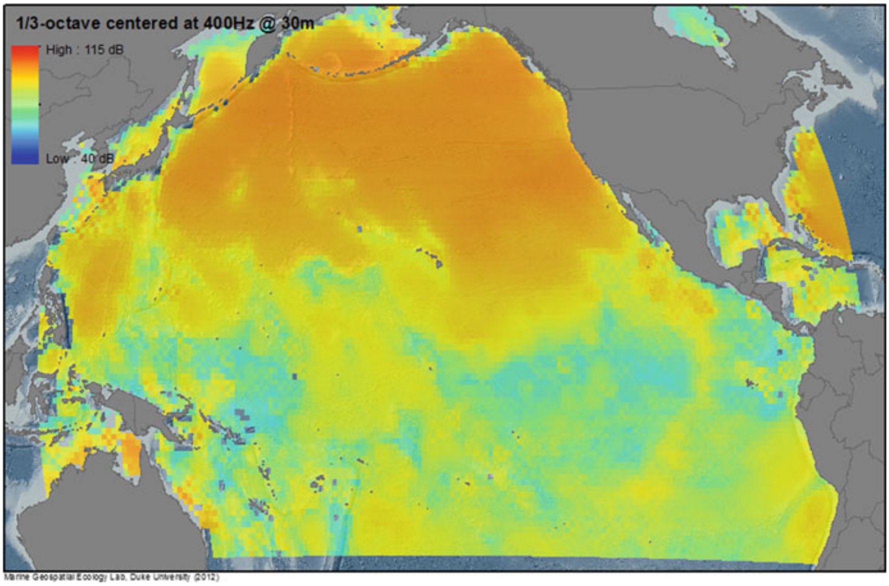


Fig. 48.1 Representative product of the Underwater Sound Field Mapping Working Group (SoundMap), illustrating the annual average predicted noise from global shipping and passenger vessel traffic in the North Pacific Ocean basin

Chapter 40 by Gedamke et al. specifically describes the SoundMap effort in more detail. Figure 48.1 provides a representative SoundMap product.

1.2 CetMap

The specific objective of CetMap was to create comprehensive and easily accessible regional cetacean density and distribution maps that are time and species specific, ideally using survey data and models that estimate density using predictive environmental factors. Additionally, to augment the more quantitative density and distribution products and provide additional context for marine mammal impact analyses, the CetMap also identified biologically important areas (BIAs), which include feeding and reproductive areas, migratory corridors, and areas in which small and resident populations are found.

CetMap Density and Distribution Mapping

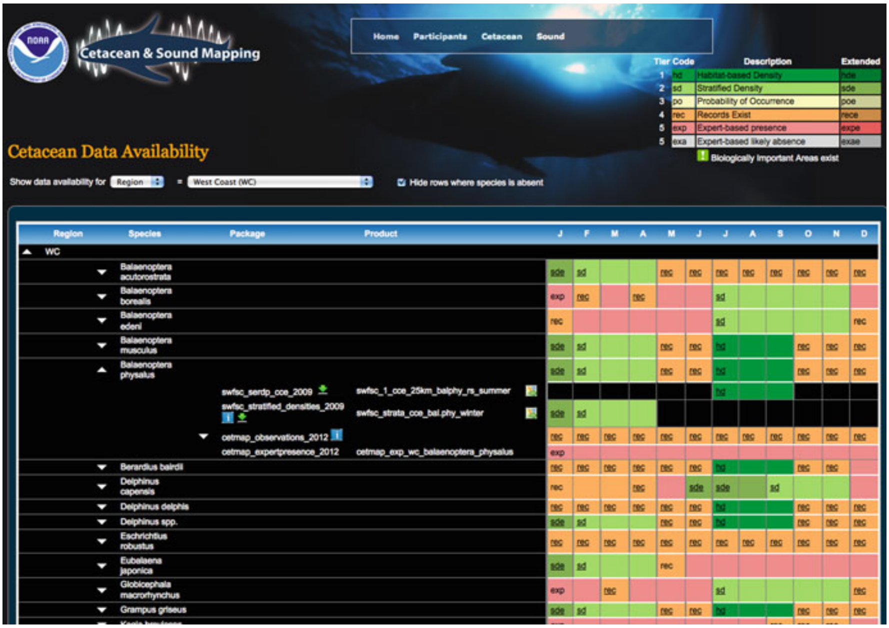
To depict the most comprehensive density and distribution maps, the CetMap group undertook five tasks where they (1) identified a hierarchy of preferred density and distribution model or information types; (2) conducted a cetacean data availability assessment that included making previously less accessible data available through this effort; (3) modeled or remodeled density using first-tier habitat-based density models in some critical areas based on updated methods and/or new data; (4) created standardized geographic information system (GIS) files from the new modeling results and other existing modeling results; and (5) developed a NOAA Web site interface that organizes these datasets and maps to highlight the best available information type, makes them searchable by region/species/month, and provides many of the GIS files for download.

First, the CetMap identified and broadly evaluated the information types and modeling methods available for estimating marine mammal density and distribution and ranked them in the following tiers based on their expected ability to accurately predict density, distribution, or presence in a spatially and temporally explicit manner: (1) habitat-based density models; (2) stratified density models; (3) probability of occurrence models; (4) records of presence, which include visual observations, acoustic detections, or satellite tagging indicators; and (5) expert knowledge.

Next, the CetMap undertook a data availability assessment in which they (1) identified and compiled existing cetacean density models, some of which were not previously available to the public; (2) identified and compiled existing indicators of cetacean presence, including visual observations, acoustic detections, and satellite tagging data (also not all previously available to the public and several expanding the known ranges of certain species; and (3) organized the available modeling results and data in a manner that allows the user to quickly identify what type of data is available for a species/region/month and where data gaps exist.

In addition to the compilation described above, the CetMap identified and undertook two key modeling efforts (expected to be finalized in the coming months) to improve the understanding of cetacean density and distribution in the US EEZ. In the Beaufort and Chukchi Seas, the CetMap is using a long-term survey dataset to produce habitat-based density models for the species commonly found there (not previously available for cetaceans in this region). For all cetacean species in the Atlantic Coast and Gulf of Mexico regions, Duke created new habitat-based density estimates for CetMap using recent survey data provided by NOAA's Northeast and Southeast Fisheries Science Center staff as well as revised modeling methods.

Finally, Duke, in collaboration with CetMap, created standardized GIS files for existing model results compiled for this effort but for which GIS maps had not previously been generated; in addition, Duke is working on the GIS files for the new modeling results that are still in production. Furthermore, CetMap worked with NOAA's Office of Science and Technology to develop the dedicated Web site through which to access both the CetMap and CetSound GIS products. The Web site includes the methods, assumptions, and metadata associated with all of the maps and provides access to downloadable shape files. Figure 48.2 shows a screen shot from the CetMap Web site.



Tier	Code	Description	Extended
1	hd	Habitat-based Density	hde
2	sd	Stratified Density	sde
3	po	Probability of Occurrence	poe
4	rec	Records Exist	rece
5	exp	Expert-based presence	expe
5	exa	Expert-based likely absence	exae

! Biologically Important Areas exist

Cetacean Data Availability

Show data availability for Region = West Coast (WC)

☑ Hide rows where species is absent

Region	Species	Package	Product	J	F	M	A	M	J	J	A	S	O	N	D
WC															
	Balaenoptera acutorostrata			sde	sd			rec	rec	rec	rec	rec	rec	rec	rec
	Balaenoptera borealis			exp	rec		rec			sd					
	Balaenoptera edeni			rec						sd					rec
	Balaenoptera musculus			sde	sd			rec	rec	hd			rec	rec	rec
	Balaenoptera physalus			sde	sd			rec	rec	hd			rec	rec	rec
		swfsc_serdp_cce_2009	swfsc_1_cce_25km_balphy_rs_summer							hd					
		swfsc_stratified_densities_2009	swfsc_strata_cce_bal.phy_winter	sde	sd										
		cetmap_observations_2012		rec	rec	rec	rec	rec	rec	rec	rec	rec	rec	rec	rec
		cetmap_expertpresence_2012	cetmap_exp_wc_balaenoptera_physalus	exp											
	Berardius bairdii			rec	rec	rec	rec	rec	rec	hd			rec	rec	
	Delphinus capensis			rec			rec		sde	sde		sd			
	Delphinus delphis			rec	rec	rec	rec	rec	rec	hd			rec	rec	rec
	Delphinus spp.			sde	sd			rec	rec	hd			rec	rec	rec
	Eschrichtius robustus			rec	rec	rec	rec	rec	rec	rec	rec	rec	rec	rec	rec
	Eubalaena japonica			sde	sd			rec							
	Globicephala macrorhynchus			exp		rec				sd					rec
	Grampus griseus			sde	sd			rec	rec	hd			rec	rec	rec

Fig. 48.2 Screen shot from Cetacean Density and Distribution Mapping Working Group (CetMap) Web site showing searchable format for accessing density and distribution data with associated shape files and metadata

CetMap BIAs

The BIA component of the CetMap effort supplements the quantitative information on cetacean density, distribution, and occurrence by (1) identifying areas where cetacean species or populations are known to concentrate for specific activities or be range limited but for which there are not sufficient data for their importance to be reflected in the quantitative mapping effort; and (2) providing additional context within which to examine potential interactions between cetaceans and human activities.

Regional experts were asked to compile the best available information from the scientific literature (e.g., books, peer-reviewed articles, and government or contract reports), unpublished data (sighting, acoustic, tagging, genetic, photo identification), and expert knowledge to create written summaries and maps highlighting areas shoreward of the US EEZ that are biologically important to cetacean species (or populations) either seasonally or year-round.

For cetacean species with distinct migrations that separate feeding and breeding areas, three types of BIAs were identified: (1) reproductive areas: areas and months within which a particular species or population selectively mates, gives birth, or is found with neonates or other sensitive age classes; (2) feeding areas: areas and months within which a particular species or population selectively feeds; these areas may be found either consistently in space and time or may be associated with ephemeral features that are less predictable but can be delineated and are generally located within a larger identifiable area; and (3) migratory corridors: areas and months within which a substantial portion of a species or population is known to migrate; the corridor is typically delimited on one or both sides by land or ice. A fourth type of a biologically important area was also identified (not limited to species that undertake distinct migrations that separate breeding and feeding areas): Small and resident population: areas and months within which small and resident populations occupying a limited geographic extent exist.

For each region and species or population with known areas of biological importance, information is presented in a written summary with an associated map and metadata table. The metadata table details the type and quantity of information used to define the important area, providing a transparent method for evaluating the important area designation. Additionally, the caveats and assumptions associated with the development of the BIAs are described on the Web site.

The CetMap is currently preparing to submit the results of the BIA effort to a journal for peer review. In the meantime, the BIAs for Hawaii have been posted on the Web site as an example of the results from the BIA exercise.

1.3 Multistakeholder Workshop

In May 2012, in Washington, DC, near-final CetMap and SoundMap products were presented at a symposium entitled *Mapping Cetaceans and Sound: Modern Tools for Ocean Management.* Attending the symposium were ~170 participants from government agencies, regulated industries, environmental consultancies, media, and conservation advocacy groups in addition to independent scientists. The discussion focused on improvement, maintenance, and growth of the overarching effort of both the CetMap and SoundMap (referred to as CetSound) products to ensure maximum utility to regulators and noise-producing entities in analysis, planning, management, and incorporation of new science within the context of noise, anthropogenic impacts, and the multiuse ocean environment.

The symposium provided an open and positive forum to share SoundMap and CetMap products and brainstorm potential management solutions with participants from a wide range of engaged constituencies. The effort received broad support for both the work conducted and the open process. Participants emphatically supported the need to continue to move forward with the maintenance and development of the SoundMap and CetMap tools.

From this discussion, several recommendations/themes arose, including: institutionalization and integration of the CetSound effort within NOAA-wide goals and programs, creation of forums and mechanisms to receive external input and funding, and outreach and education. For more information, please see a full report from this workshop available at http://cetsound.noaa.gov/pdf/CetSound_Symposium_Report_Final.pdf.

2 NOAA Ocean Noise Strategy

Following the broad positive reception of the CetSound mapping tools across multiple stakeholder groups, the then NOAA Administrator Dr. Jane Lubchenco encouraged the development of a 10-year NOAA ocean noise strategy. In support of this goal, a staff-level ocean noise strategy team was identified and a vision for successfully addressing ocean noise issues was described. Successful implementation of a NOAA ocean noise strategy will mean that the following four visionary components have been achieved. (1) Integrated NOAA management actions are reducing the chronic and cumulative effects of noise. (2) NOAA and others are conducting research to fill critical gaps and best informed management decisions. (3) NOAA is developing publicly available tools to support assessment, planning, and mitigation for noise-making activities across large spatial and temporal scales. (4) NOAA is promoting public understanding of noise impacts in the United States and abroad.

After the articulation of this vision, the strategy team worked to identify the broad steps necessary to achieve it, which, in addition to finalizing the initial CetSound products, included (1) organizing a larger cross-NOAA team to identify noise conservation goals to guide both science planning and prioritization and management decisions under multiple authorities; (2) creating new or utilizing existing external forums (Federal, nongovernmental stakeholders, international) to solicit input and maximize synergy with related efforts; (3) maintaining and developing mapping tools to support agency decision making as well as activity planning and science prioritization for external groups; and (4) implementing outreach and education on ocean noise and NOAA's goals for reducing its impacts.

2.1 Internal Cross-NOAA Team

In February 2013, the noise strategy team convened a diverse group of scientific experts, regulatory practitioners, managers, and lawyers who are knowledgeable in the field of ocean noise and represent multiple programs or authorities through which NOAA regulates or researches ocean noise. The objectives of bringing this team together were to (1) identify NOAA's long-term conservation goals for addressing ocean noise; (2) explore management actions under NOAA's multiple authorities that could contribute toward these goals; (3) prioritize science needs associated with these larger conservation goals and management actions; (4) inform the continued development of CetSound tools to support management decisions and science prioritization; and (5) prioritize education and outreach needs associated with these objectives.

Over the course of the 2-day meeting, the group converged around a theme that signifies a new approach for addressing noise that better acknowledges NOAA's growing concern regarding the impacts of chronic and cumulative noise exposure. Specifically, the group recognized that NOAA's management goals and actions must address the conservation of acoustic habitat quality in addition to the more traditional focus on the minimization of physical and behavioral impacts to specific species.

Action items were identified and included the near-term development (currently in progress) of three white papers that (1) articulate and support NOAA's growing recognition of the potential effects of chronic noise exposure and the importance of acoustic habitat, (2) outline the status of the species-focused science and management of ocean noise impacts across multiple taxa within NOAA's jurisdiction, and (3) describe methods and capabilities for characterizing soundscapes. These papers are intended to inform the prioritization of noise science/data needs and management actions and to ultimately inform the development of an over-arching ocean NOAA noise strategy framework. This framework will outline the agency's management and science themes and goals and recommend processes for identifying specific implementation actions.

2.2 Next Steps

The most immediate next steps are for the cross-NOAA writing teams to complete the development of the three white papers identified in Section 2.1. These papers will feed into the development of the noise framework. However, coordination and engagement with external entities (Federal agencies, NGOs, and other stakeholders) are also needed to inform the development of the noise framework, which will prioritize the science and management goals within NOAA and describe the adaptive mechanisms for accomplishing them. NOAA has begun exploring ways to coordinate externally on these noise issues, for example, through development of and engagement in the Subcommittee on Ocean Science and Technology's Interagency Task Force on Ocean Noise and Marine Life.

As the science and management goals related to ocean noise impacts are being identified and prioritized, NOAA, in coordination with external partners, is also working toward (1) the installation of an additional information technology (IT) infrastructure to support further analytical capabilities for CetSound tools and database/archiving needs; (2) the creation of an external funding mechanism for prioritized research and mapping tools (e.g., National Oceanographic Partnership Program); and (3) a plan for the development of outreach and educational tools.

Chapter 49
Understanding the Population Consequences of Acoustic Disturbance for Marine Mammals

John Harwood, Stephanie King, Cormac Booth, Carl Donovan, Robert S. Schick, Len Thomas, and Leslie New

Abstract Loud anthropogenic underwater noise, such as that associated with sonar operations, pile driving, or seismic surveys, can cause behavioral and physiological disturbance to many animals that may affect their survival or ability to breed. However, no formal framework for assessing the population-level consequences of this disturbance is currently available. We describe an interim version of a framework developed by a working group on the population consequences of disturbance, funded by the US Office of Naval Research through the University of California, that can be used to assess the effects of offshore renewable energy developments on marine mammal populations.

Keywords Renewable energy • Noise

1 Introduction

There is increasing evidence that loud noise generated by activities such as sonar operations, pile driving, and seismic surveys can affect the behavior of marine mammals. Southall et al. (2007) reviewed the historical evidence for this, and more recent examples include Tougaard et al. (2012), DeRuiter et al. (2013), and Goldbogen et al. (2013). Behavioral disturbance may have a direct effect on the

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survival probability of an individual female's offspring if it results in her being separated from her calf, and it may have an indirect effect on the probabilities of survival and reproduction if it results in a decrease in energy intake or an increase in energy expenditure. For example, observed declines in bottlenose dolphin (*Tursiops truncatus*) populations subject to disturbance from tourist boats appear to be linked to a decrease in the amount of time spent resting by mothers with calves, an activity with relative low-energy demands (Lusseau 2003, 2004). Behavioral disturbance may also result in animals being displaced temporarily from preferred, and potentially critical, habitats. This could have a direct effect on survival if they are displaced into an area where the risk of predation is elevated and an indirect effect on survival and reproduction if they are displaced into an area where prey is less abundant or more difficult to capture, thus reducing their energy intake.

In addition, anthropogenic noise can induce other physiological effects, such as a temporary or permanent (PTS) shift in hearing thresholds or changes in levels of stress-related hormones. For example, Rolland et al. (2012) reported a decline in levels of stress-related hormone metabolites in feces collected from North Atlantic right whales (*Eubalaena glacialis*) in the Bay of Fundy, Canada, immediately after 11 September 2001, when the average underwater noise levels decreased by 6 dB in association with a dramatic reduction in boat traffic. This implies that high levels of underwater noise may result in elevated stress levels in some baleen whale species. High stress levels have been shown to decrease survival probabilities in humans (Russ et al. 2012).

2 Population Consequences of Acoustic Disturbance, Population Consequences of Disturbance, and Interim Population Consequences of Disturbance

In 2005, a panel convened by the National Research Council (NRC) of the US National Academy of Sciences developed what they referred to as a "conceptual model" (NRC 2005) that outlined the way marine mammals respond to anthropogenic sound and how the population-level consequences of these responses could be inferred on the basis of observed changes in behavior. They called this model population consequences of acoustic disturbance (PCAD). In 2009, the US Office of Naval Research (ONR) set up a working group to transform this conceptual model into a formal mathematical one and to consider how the parameters of that model could be estimated using data from a number of case studies. The working group extended the PCAD model to consider forms of disturbance other than noise and to address the impact of disturbance on physiology as well as on behavior. The current version of their model, which is based on case studies of northern and southern elephant seals (*Mirounga angustirostris* and *M. leonine*, respectively), coastal bottlenose dolphins, North Atlantic right whales, and beaked whales (family Ziphiidae), is now known as population consequences of disturbance (PCoD). It is shown in Fig. 49.1a and described in more detail by New et al. (2014).

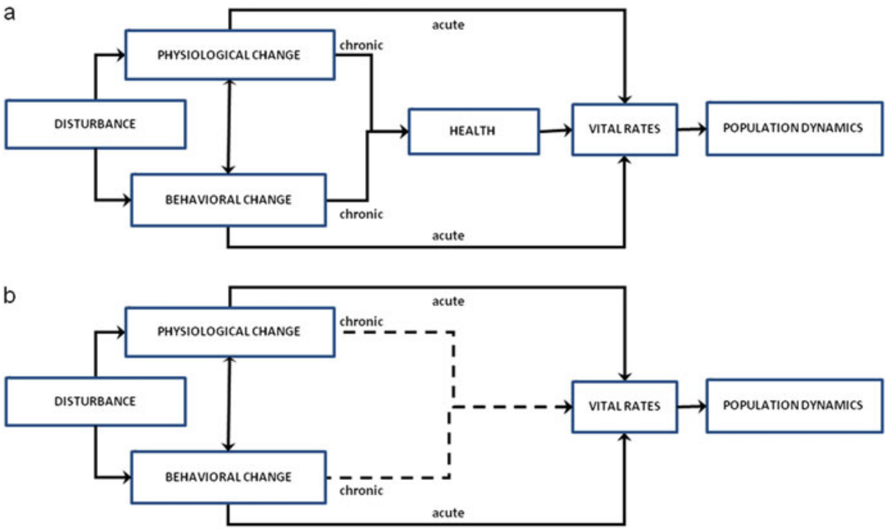

Fig. 49.1 (**a**) Framework for modeling the population consequences of disturbance (PCoD) developed by the Office of Naval Research (ONR) working group on population consequences of acoustic disturbance (PCAD; modified from New et al. 2014, Fig. 5). The term "health" is used to describe all aspects of the internal state of an individual that might affect its fitness. These could include, for example, the extent of its lipid reserves or its resistance to disease. "Vital rates" refers to all the components of individual fitness (probability of survival and producing offspring, growth rate, and offspring survival). (**b**) A simplified version of the PCoD framework used in the interim PCoD approach. *Dotted lines*, functions that determine the chronic effects of physiological and behavioral change on vital rates, indicating that their form is determined using the results of an expert elicitation process rather than empirical evidence

The new conceptual model shows how changes in an individual's behavior and physiology may affect its vital rates (e.g., the probability of adult and offspring survival, probability of giving birth) either directly (an acute effect) or indirectly (a chronic effect) via its health (defined as all aspects of the internal state of an individual that might affect its fitness).

New et al. (2013a, b, 2014) used case studies of bottlenose dolphins (New et al. 2013a), beaked whales (New et al. 2013b), and southern elephant seals (New et al. 2014) to show how changes in behavior in response to disturbance could affect the energy reserves of adult females and how these changes might affect the probability of giving birth and offspring survival. The consequences of these changes for population dynamics could then be inferred from the number of animals that might be affected by disturbance and the size of the population of which they are a part. Nabe-Nielsen et al. (2011) used a similar approach to assess the potential impacts of wind farm operation on harbor porpoises (*Phocoena phocoena*) in inner Danish waters.

Unfortunately, the empirical information that is required to estimate the parameters of the full PCoD model is not available for most marine mammal species. We have therefore developed a simplified, interim version of the PCoD model (Fig. 19.1b) in which the information required to quantify the potential effects of behavioral and physiological changes on vital rates, shown by the dotted lines in Fig. 49.1b, was obtained using a formal expert elicitation process (e.g., Aspinall 2010), which is described in detail in Chapter 27 by Donovan et al. Thompson et al. (2013) have independently developed an informal version of this approach to assess the effects of pile driving on a harbor seal population.

3 The Interim PCoD Framework

Expert elicitation is a technique that has been widely used in conservation science when there is a relative lack of data but an urgent need for conservation decisions (Martin et al. 2012). We developed our elicitation procedure in collaboration with Professor Mark Burgman, director of the Australian Centre of Excellence for Risk Analysis at the University of Melbourne, who has worked closely with the PCAD working group. In particular, we used the four-step interval approach developed by Speirs-Bridge et al. (2010) to provide reliable estimates of the confidence that experts attached to their opinions.

We asked experts to focus on the potential population consequences of PTS and disturbance that might be associated with offshore renewable energy developments. We hypothesized that the most likely vital rates to be affected by PTS are survival (for all age classes) and the probability of giving birth and that disturbance was most likely to affect calf and juvenile survival and the probability of giving birth. We therefore only asked the experts for their opinions of the effects of PTS and disturbance on these vital rates. We defined disturbance as any behavior with a score of 5* or higher on the behavioral response severity scale drawn up by Southall et al. (2007).

Experts were asked to choose values for three parameters (the number of days of disturbance required to have any effect on a vital rate, the maximum likely change in that vital rate as a result of disturbance, and the number of days of disturbance required for that maximum effect) that determined the shape of a simple relationship between the level of disturbance experienced by an individual in a year and each vital rate. This relationship is highly simplified but, in the absence of any empirical data on the shape of this relationship for most marine mammal species, it is hard to justify proposing a more complex form.

The resulting relationships were then incorporated into stage-structured stochastic population models similar to those used in population viability analyses (Morris and Doak 2002), which we developed for five species (harbor seal, gray seal [*Halichoerus grypus*], harbor porpoise, bottlenose dolphin, and common minke whale [*Balaenoptera acutorostrata*]). It should be recognized that many elements of these models are based either on strong assumptions or on the opinions of the experts we consulted rather than on empirical data. There is clearly an urgent need to collect the information that would allow more realistic estimates of the parameters that define these relationships to be made. Such information may be obtained by monitoring the effects of developments (see below), but a dedicated research program is more likely to provide a comprehensive set of data.

The models also attempt to capture many of the major sources of uncertainty involved in the calculations of the potential effects of offshore renewable energy development on marine mammal populations. These include (1) uncertainty about the size of the marine mammal population affected by the development; (2) uncertainty about what proportion of that population will be vulnerable to the effects of the development; (3) uncertainty in the predictions of the number of animals that will experience disturbance and PTS as a result of 1 day of construction or operation; (4) uncertainty about the predictions of the total number of days of disturbance an individual animal will experience during the course of construction of a development and of the total number of animals that will experience PTS; (5) uncertainty about the effects of disturbance and PTS on vital rates; and (6) the effects of demographic stochasticity and environmental variation.

The population models were then used to forecast the effects of the planned developments on the dynamics of each population over a specified number of years. We performed many hundreds of simulations for each development scenario, sampling at random from statistical distributions that captured the different sources of uncertainty. For each simulation, we compared the forecast dynamics of two populations, both of which experienced the same history of environmental variation and had identical demographics but one of which experienced the predicted effects of disturbance. A wide range of output statistics can be produced from these computer simulations. We believe the most useful of these are the statistical distributions of the forecasts of the change in population size as a consequence of disturbance (calculated by comparing the forecasts of paired identical populations with and without disturbance) over different time horizons and estimates of the probability that a disturbed population will decline by a specified amount (for example, by >5%) over a particular time interval.

4 Implementing the Interim PCoD Protocol

The protocol we developed for implementing this interim approach requires estimates of the number of animals likely to be exposed to sound levels that could result in death or injury in PTS and in behavioral disturbance during 1 day of construction or operation of a particular development, preferably with an indication of the uncertainty associated with these estimates. In addition, it requires an approximate timetable for the events that are involved in construction work (e.g., the planned number of days on which piling is expected to occur in each month of the year) for each development. It is possible to investigate the effects of multiple developments, involving a range of renewable energy technologies on the same marine mammal population over many years. For example, the protocol can be used to assess the cumulative effects of the construction of a number of different offshore wind farms, the operation of several different tidal turbine arrays, and mortality associated with by-catch in fisheries. Careful monitoring of the effects of any developments that are actually permitted can then provide insight into the

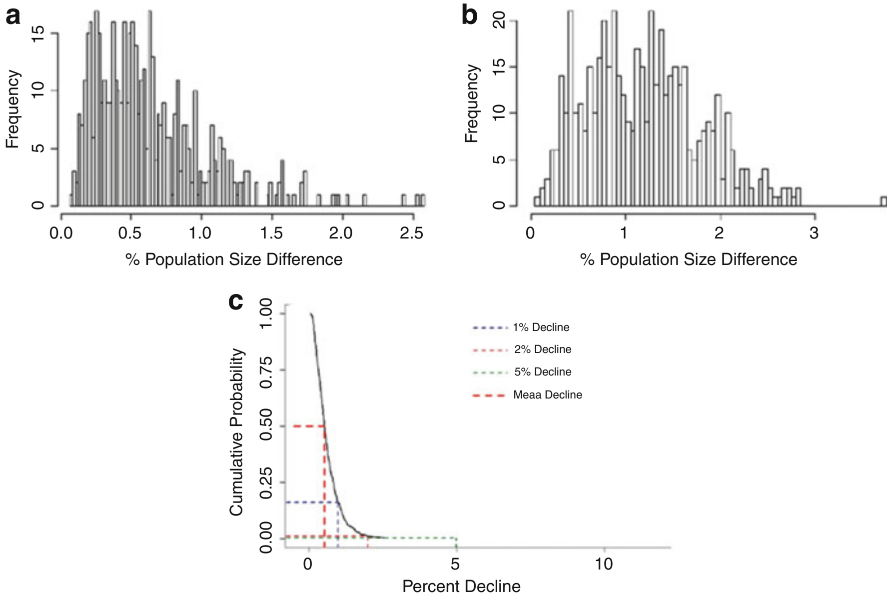

Fig. 49.2 Predicted effects of disturbance and permanent threshold shift (PTS) on 500 simulated minke whale populations associated with the construction of 2 hypothetical wind farms when all members of the population were vulnerable to the effects associated with both wind farms. (**a**) Predicted differences between the size of the undisturbed and disturbed populations immediately after construction expressed as a percentage of the population size before the start of construction. (**b**) Predicted effects 6 years after construction. (**c**) Proportion of simulated populations that experienced declines of at least 1%, at least 2%, and at least 5% at the end of the construction period and the mean decline in abundance over this period

validity of the forecasts of the model and allow direct estimation of the parameters of some of the relationships between disturbance and vital rates using empirical data rather than expert opinion.

Figure 49.2 shows a purely hypothetical example of the predicted effect on the population of common minke whales in UK coastal waters associated with the construction of two wind farms placed at arbitrary locations off the east coast of Scotland. The hypothetical construction work involved 52 days of piling at each site in the first year and 42 days of piling in the second year. Most of the simulated populations showed a decline <1% immediately after the cessation of construction and none showed a decline >3%.

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Chapter 50
Multiple-Pulse Sounds and Seals: Results of a Harbor Seal (*Phoca vitulina*) Telemetry Study During Wind Farm Construction

Gordon D. Hastie, Debbie J.F. Russell, Bernie McConnell, Dave Thompson, and Vincent M. Janik

Abstract Offshore construction and survey techniques can produce pulsed sounds with a high sound pressure level. In coastal waters, the areas in which they are produced are often also used by seals, potentially resulting in auditory damage or behavioral avoidance. Here, we describe a study on harbor seals during a wind farm installation off southeast England. The study used GPS/global system for mobile communication tags on 23 harbor seals that provided distribution and activity data; the closest range of individual seals to piling varied from 6.65 to 46.1 km. Furthermore, the maximum predicted received levels (RLs) at individual seals varied between 146.9 and 169.4 dB re 1 μPa peak to peak.

Keywords Pinniped • Propagation • Offshore wind farm • Renewables

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1 Background

1.1 Pulsed Noise in the Marine Environment

Man-made pulsed sounds are now commonplace in the marine environment; these are either produced intentionally (e.g., seismic surveys or sonar) or as a by-product of an activity (e.g., explosives or pile driving). The production of such sounds is likely to increase in the coming years as the petroleum industry expands into new offshore areas and with ambitious renewable energy targets in many countries, offshore wind farm construction will increase. Pulsed sounds from these activities are some of the most powerful produced underwater; for example, peak-to-peak (pp) source noise levels of pile driving monitored by Nedwell et al. (2007) ranged between 243 and 257 dB re 1 μPa_{pp} at 1 m. Similarly, source levels of seismic pulses have been estimated up to ~263 dB re 1 μPa_{pp} at 1 m (Gordon et al. 2004).

The production of these sounds has raised concerns about potential adverse impacts on some marine mammals; many proposed development areas overlap with the at-sea distribution of seals and pulsed sound appears to have the potential to elicit overt behavioral responses (Gordon et al. 2004).

Dedicated studies of the at-sea behavior of seals in response to pulsed sound are extremely limited. However, a small number of observational studies of animals at the surface around industrial activity exist; for example, sightings rates of ringed seals (*Phoca hispida*) from a seismic vessel in shallow Arctic waters showed no difference between periods with the full array, partial array, or no guns firing (Harris et al. 2001). Similarly, observation of ringed seal behavior during impact pipe-driving sounds in Alaska revealed that they exhibited little or no reaction, swimming near to the activities throughout construction and as close as 46 m from the pipe-driving operation (Blackwell et al. 2004).

In one of the few dedicated behavioral studies on individual responses to pulsed sounds, Thompson et al. (1998) carried out controlled exposures using small seismic air guns (source level [SL], 215–224 dB re 1 μPa_{pp} at 1 m) to harbor and gray seals (*Halichoerus grypus*) fitted with telemetry devices. These provided information on the movement, dive behavior, and swim speeds of the seals throughout the exposures. In contrast to the studies described above that showed an apparent lack of a response by animals (Harris et al. 2001; Blackwell et al. 2004), in six of eight trials with harbor seals, the animals exhibited strong avoidance behavior, swimming rapidly away from the source. Stomach temperature tags indicated that they also ceased feeding during this time. Only one seal showed no detectable response to the guns and approached to within 300 m of them. Similar avoidance responses were documented during all the trials with gray seals; they changed from making foraging dives to V-shaped transitting dives and moved away from the source. It was suggested that the responses to more powerful commercial arrays might be expected to be more extreme, longer lasting, and occurring at greater ranges.

Recent research by Götz and Janik (2011) provides insights into the physiological basis of the responses by seals that is highly relevant to multiple-pulsed sound. This work highlighted the role of the mammalian startle reflex, a fast motor response that is elicited if a stimulus has a sudden onset and exceeds a certain intensity threshold (Yeomans et al. 2002) that may facilitate a flight response. The startle reflex can be elicited by stimuli with certain acoustic parameters that pulsed sound often exhibits. For example, in rats, the acoustic startle requires a stimulus to reach an intensity of 80–90 dB above the hearing threshold within about 15 ms of its onset (Flesher 1965). Götz and Janik (2011) presented evidence of spatial avoidance behavior in captive gray seals to a “startle pulse” (a band-limited sound pulse with a peak frequency of 950 Hz spanning ~2 octaves); received levels ranged from 170 to 174 dB re 1 μPa.

Important when considering the multipulsed nature of sounds from seismic surveys or pile driving is that Götz and Janik (2011) presented evidence that repeated elicitation of the acoustic startle reflex leads to a rapid and pronounced sensitization (an increased responsiveness to a stimulus) of sustained spatial avoidance behavior in gray seals. Seals developed rapid flight responses, left the exposure pool, and showed clear signs of fear conditioning. Once sensitized, seals even avoided a known food source that was close to the sound source. In contrast, animals exposed to nonstartling (long rise time) stimuli of the same maximum sound pressure habituated, and flight responses waned or were absent from the beginning. The authors concluded that startle-eliciting noise pulses have the potential to cause severe effects on long-term behavior, individual fitness, and longevity of individuals in wild animal populations (Götz and Janik 2011); this has clear implications for the repeated use of pulsed noise during activities such as seismic surveys or pile driving.

In response to the relative paucity of empirical data on the at-sea behavior of seals in response to pulsed sound, we carried out a study on harbor seal behavior during the construction of the Lincs Offshore Wind Farm in the North Sea.

2 Methods

2.1 Telemetry

To measure the movements and proximity of seals at sea to pile driving, GPS/global system for mobile communication (GSM) tags (McConell et al. 2010) were deployed on 25 harbor seals in the Wash, southeast England, in January 2012 and stayed on the animals for up to 5.5 month. The GPS/GSM tags are data loggers that attempt to record the location of a seal at regular intervals using a hybrid GPS system. Stored location and behavioral data are opportunistically relayed ashore by means of an embedded mobile phone (GSM) modem when the tag comes within mobile phone coverage. These tags provided fine-scale distribution and activity data (seal locations approximately every 15 min), allowing the investigation of movements during pile driving.

Seals were captured while hauled out on intertidal sandbanks. Once captured, the seals were anesthetized with Zoletil or Ketaset. The tags were attached to the fur at the back of the neck using a rapid-setting epoxy resin. A series of morphometric measurements and biological samples were taken.

2.2 Pile Driving

Throughout the period of tag deployment, a total of 31 pile foundations (5-m-diameter piles) were installed using impact pile driving at the Lincs Offshore Wind Farm. The pattern of piling was characterized by intermittent periods of piling (~4–5 h in length) followed by gaps of between a few hours to a few days. Within an individual pile installation, the blow energy was generally characterized by a "ramp up" in blow energy. In general, there is a gradual ramp up to ~700 kJ over the first 60 min before increasing to a full blow energy of ~2,000 kJ for the remaining installation.

To estimate pile-driving SLs, peak-to-peak SLs, estimated by Nedwell et al. (2011) during the installation of piles at the same wind farm, were corrected for changes in blow energy using recordings made with an autonomous moored sound recorder (DSG-Ocean Acoustic Datalogger, Loggerhead Instruments). Received levels (RLs) at each seal were then estimated using data on the timing and associated blow energy for every piling blow using range-dependent acoustic models (Collins 1993) that account for the geoacoustic properties of the subbottom and the discontinuity of these properties at the interface (Jensen et al. 1994); modeling was carried out using the RAMSGeo model in the acoustic toolbox user-interface and postprocessor (AcTUP V2.2 L, Curtin University, Perth, Australia) software. Transmission loss was calculated at 1-km intervals along 5° radii from the piling source location out to a range of 120 km; seal locations were then matched to the predicted RLs at interpolated 1-s intervals along each seal's track. The RLs were validated using a series of boat-based hydrophone recordings during the installation of one of the piles. Recordings were made between 1,000 and 9,500 m from the piling; overall mean error in the predictions at these ranges was 3.3 ± 1.7 (SD) dB re 1 μPa_{pp}.

3 Results

At the end of January 2012, 25 GPS/GSM tags were deployed, of which 22 stayed operational on the animal for over 1 week. All data were cleaned according to Sea Mammal Research Unit (SMRU) protocol (Russell et al. 2011). Throughout the study, the seals regularly moved between haul-out sites on sandbanks around the Wash to areas offshore. During these transits to sea, the seals routinely swam past the wind farm site. The seals were also at sea during pile-driving events; the closest distance of individual seals to active pile-driving locations varied between 6.7 and 46.1 km. All seals therefore also received sound from the pile driving, with maximum predicted RLs at individual seals varying between 146.9 and 169.4 dB re 1 μPa_{pp}.

4 Discussion

Our study illustrates the value of telemetry-based studies to understand the behavior of a wide-ranging species and the potential impacts of anthropogenic sound on movements.

In general, seals made regular movements between haul-out sites on intertidal sandbanks and areas offshore (presumed to be used for foraging). Furthermore, each seal was present in offshore areas during pile driving at some point during the study. Although the seals continued to transit between the haul outs and areas at sea during the study, it should be noted that no seals came closer than 6.7 km to the piling location when pile driving was being carried out. However, without full analyses of behavioral metrics, it is currently unclear whether the patterns of movement and activity are significantly different between periods of piling and nonpiling. Nevertheless, data on the movements by seals around sound fields such as these provide an opportunity for a detailed assessment of levels that may elicit behavioral responses and allow the investigation of the implications of such movements on physiological effects such as auditory damage.

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Chapter 51
Developing Sound Exposure Criteria for Fishes

Anthony D. Hawkins and Arthur N. Popper

Abstract In assessing the impact of aquatic developments, it is important to evaluate whether accompanying underwater sounds might have adverse effects on fishes. Risk assessment can then be used to evaluate new and existing technologies for effective prevention, control, or mitigation of impacts. It is necessary to know the levels of sound that may cause potential harm to different species from different sources as well as those levels that are likely to be of no consequence. The development and use of impact criteria are still at an early stage for fishes.

Keywords Sound • Behavior • Impact • Injury • Pile driving

1 Introduction

In many countries, legislation now requires the assessment of potential impacts on aquatic life of in-water sound-producing activities. However, few scientific data are available regarding the effects of sounds on fishes. Moreover, there are few guidelines on appropriate assessment procedures and potential mitigation measures. This paper provides an overview of issues that require understanding if criteria are to be developed for the effects of man-made sounds on fishes. Only limited references are provided. Much of the literature on the effects of sound on fishes was reviewed by Popper and Hastings (2009) and in a more recent review prepared by Normandeau Associates (2012).

Prerequisites for evaluating the effects include (1) a description of the sound-producing activities and the characteristics of the sounds produced; (2) knowledge of prevailing background noise levels in the environment; (3) prediction of the

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Table 51.1 Potential effects resulting from sound exposure

Impact	Effects on animal
Mortality	Death from damage sustained during sound exposure
Injury to tissues; disruption of physiology	Damage to body tissue, e.g., internal hemorrhaging, disruption of gas-filled organs like the swim bladder, consequent damage to surrounding tissues
Damage to the auditory system	Rupture of accessory hearing organs, damage to hair cells, permanent threshold shift, temporary threshold shift
Masking	Masking of biologically important sounds including sounds from conspecifics
Behavioral changes	Interruption of normal activities including feeding, schooling, spawning, migration, and displacement from favored areas

The actual sound levels and distances from the sources at which each of the effects may be found will vary depending on the actual sound level and distance

transmission of sound from various man-made sources; and (4) consideration of any effects on fishes at different locations relative to the source.

In looking for impacts, it is especially important to distinguish between minor effects that elicit only transient changes in behavior and those that materially affect the well-being of individual fishes and of fish populations. The potential effects resulting from sound exposure are summarized in Table 51.1

As part of the process of risk assessment, it is necessary to determine the levels of sound that have particular effects from different types of sources. The goal is to provide criteria to serve as threshold values, expressed in an appropriate acoustic metric, above which the onset of effects might occur or a particular level of damage be incurred. Both the effects and the metric itself must be specified clearly. The development and use of these criteria are at an early stage, however, and neither the degree of damage nor the metrics to be used have been clearly defined in the past. Moreover, no formal consensus currently exists on the measurement and evaluation of the effects of underwater sounds. Different terms and metrics are used in different contexts. The purpose of this paper is to not provide criteria or guidelines for sound exposure for fishes but to provide an outline of the issues that need to be considered in developing such criteria. A fuller treatment of guidelines and information gaps can be found in Popper et al. (2014) and Hawkins et al. (2015).

2 Sound Sources

Underwater sounds may be divided into continuous and impulsive signals. Continuous sounds can be tonal or broadband and some may be intermittent. Some continuous sounds may be "'rougher" than others and are potentially more damaging than other continuous sounds. Examples of sources producing continuous sounds include ships; aircraft; machinery operations such as drilling, operational wind turbines and tidal generators; dredging; and some active sonar systems.

In contrast, impulsive sounds are brief broadband transients (e.g., explosions, seismic air gun pulses, and pile-driving strikes). Near their source, such sounds have a rapid rise time, reach a maximum value, and are followed by decay. With increasing distance, the time structure becomes drawn out and less "sharp" or less impulsive in character. Impulsive sounds have the potential to be much higher in amplitude at the source than continuous sounds.

3 Metrics

A major issue in trying to describe and understand the effects of man-made sounds is how they are best described in terms that allow assessment of the energy that actually results in effects (see Chapter 3 by Ainslie and de Jong). The metrics applied to continuous sounds for estimating the likelihood of damage are the root-mean-square (rms) sound pressure, peak sound pressure, and, for many fishes, the corresponding particle motion in three dimensions. Transient sounds may be expressed in terms of their peak levels. However, rms and peak levels are not sufficient for characterizing the energy in sounds such as those generated by pile-driving strikes or the discharge of seismic airguns. Hastings and Popper (2005) proposed the use of sound exposure level (SEL), the time integral of the pressure squared for a single event, as a metric for setting pile-driving criteria (as well as for other impulsive sounds). Subsequent papers (e.g., Popper et al. 2006; Carlson et al. 2007; Popper and Hastings 2009) advocated the use of both SELs and peak levels and emphasized the need to consider the effects of repetition of the impulse and/or the rise time of the signal.

It is also now clear that assessment of sound-producing activities and the potential for impacting fish generally has to consider both cumulative and aggregate effects, that is, cumulative effects arising from repetition of a particular source, such as the repeated strikes of a pile driver, and the aggregate effects from different types of sources, such as from different pile drivers or from the combined effects of pile driving and shipping.

It is now accepted that it is necessary to take into account the potential effects not in terms of exposure to a single sound but to the accumulated energy over exposure to multiple sounds over some period of time. The metric generally used is the cumulative SEL (SEL_{cum}). This metric can be estimated from a representative single-strike SEL (SEL_{ss}) value and the number of strikes that would be required to place the pile at its final depth. However, this accumulation assumes that all strikes have the same SEL value and that a fish would continuously be exposed to pulses with the same SEL, which is never actually the case.

4 Frequency Weighting

Because animals do not hear equally well at all frequencies within their functional hearing range, weighting may be applied to measurements of sounds to quantitatively compensate for differences in their frequency response. For marine mammals, generalized frequency-weighting functions have been derived for different functional hearing groups (Southall et al. 2007). In fishes, Nedwell et al. (2007) have proposed the frequency-weighting technique for determining the level of sound relative to hearing threshold [dB_{ht}(*Species*)] as a useful metric for quantifying the level of sound experienced by different species. The dB_{ht} references the sound to the species' hearing threshold in terms of sound pressure.

However, not all or even most fishes respond to sound pressure. Many are sensitive to particle motion. Particular care must be taken in applying a dB_{ht} expressed in terms of sound pressure to species, such as the Atlantic salmon *Salmo salar*, plaice *Pleuronectes platessa*, or lemon shark *Negaprion brevirostris*, that are sensitive to particle motion because the values will not be appropriate when a fish is close to a sound source or near a reflecting boundary. It is also very important that the hearing sensitivity curves or audiograms on which dB_{ht} values are obtained under appropriate acoustic conditions are based on behavioral measurements of what a fish really hears rather than measurements of potentials generated within the central nervous system (Ladich and Fay 2013). Of the 32,000 or more extant species of fish, only a handful of audiograms have been measured under appropriate acoustic conditions using suitable threshold assessment methods. Note that frequency weighting may only be appropriate in considering detection and behavioral responses to sounds; it may not be relevant where injury from sound exposure is being assessed.

5 Sound-Propagation Modeling

To determine the sound levels to which fish will actually be exposed, it is necessary to model the propagation of sound from the source into the wider environment and also to consider any movements by the fish. The geometry of noise exposure is important. However, most models and most studies have focused on modeling acoustic pressure. Although this is suitable for marine mammals and some fishes as well as for other types of injury (e.g., barotrauma) in all fishes (see Chapter 14 by Casper et al.), hearing in most fishes involves the detection of particle motion. Thus, for fishes, models that focus on pressure alone are of limited value, at least with regard to the potential effects on sound detection. Instead, it is important to have data and models that provide insight into the particle motion emanating from a source. Modeling of the levels of particle motion to which fishes are exposed is complex and is seldom done. There is a particular lack of data on the transmission of particle motion through the seabed from sources such as impact pile driving (see Chapter 53 by Hazelwood and Macey).

Background noise in the area of interest is also important because it has the potential to mask detection by fish of biologically important signals. Some areas are already noisy as a result of shipping and other activities. Others may have characteristic soundscapes, perhaps dominated by biological sources, where it may be important to try to retain predevelopment noise levels.

6 Assessment of Effects

6.1 Injury

Exposure to high-amplitude impulsive sounds is of most concern in terms of death and injury, although there are very few instances of death shown in the literature unless the fish are within a few meters of a very intense source. Fish may be harmed by the sharp high-level sounds generated by explosions, impact pile driving, and seismic air guns. In response to concerns about such sounds, and particularly sounds from impulsive pile driving, the Fisheries Hydroacoustic Working Group (FHWG) in the United States developed interim criteria for pile driving to sound pressure levels of 206 dB re 1 µPa peak and 187 dB re 1 $\mu\text{Pa}^2\cdot\text{s}$ SEL_{cum} at 10 m for all listed fishes except those that were <2 g. In that case, the recommended SEL_{cum} is 183 dB re 1 $\mu\text{Pa}^2\cdot\text{s}$. The period of accumulation for the SEL_{cum} value is the whole pile-driving sequence. It has been suggested that a 12-h break in the pile-driving operation resets the SEL accumulation (Stadler and Woodbury 2009).

However, recent papers have provided quantitative data to define the levels of impulsive sound that could result in the onset of injury to fish (e.g., Halvorsen et al. 2012a, b; Casper et al. 2012, 2013; see also Chapter 14 by Casper et al.). A controlled-impedance fluid-filled wave tube simulated exposure to high-energy impulsive sound pressures characteristic of far-field, plane-wave acoustic conditions. Juvenile Chinook salmon (*Oncorhynchus tshawytscha*) and five other species were exposed to impulsive sounds and the injuries sustained were subsequently evaluated for different sound exposure levels (see Chapter 14 by Casper et al.). A defined level of injury (based on an index of observed injuries) was achieved for an SEL_{cum} of 210 dB re 1 $\mu\text{Pa}^2\cdot\text{s}$, suggesting that FHWG interim criteria are well below those that would result in the onset of any physiological effect.

Halvorsen et al. (2012a) were able to reject the hypothesis that the same type and severity of injury would occur for the same total energy level of exposure (SEL_{cum}) regardless of how that was reached (e.g., through many low-energy impulsive sounds or fewer high-energy impulsive sounds). Although the SEL_{cum} is the most important variable to consider, the SEL_{ss} and the number of impulses are also important. In a further paper, Halvorsen et al. (2012b) exposed three other species to simulated pile-driving sounds. Their results suggested that the type of swim bladder present in the fish was correlated with injury at higher sound levels. Casper et al. (2012; see Chapter 14 by Casper et al.) subsequently evaluated the ability of Chinook salmon to recover from injury after exposure to impulsive sounds. Their data supported the hypothesis that one or two mild injuries resulting from pile-driving exposure were unlikely to affect the survival of the exposed animals, at least in a laboratory environment. The authors also confirmed that the six very different species studied could be exposed to pile-driving sounds substantially louder than the current industry guidelines of 187 dB re 1 $\mu\text{Pa}^2\cdot\text{s}$ SEL_{cum} without sustaining injury. Casper et al. (2013) have also shown that the onset of injury to the ear (and presumably hearing loss) starts at higher SEL_{cum} levels than other injuries.

6.2 Impairment of Hearing

We have recently reviewed the effects of sound on the hearing of fishes (Normandeau Associates 2012). Because fish can regenerate lost or damaged sensory cells of the ear, it is unlikely that any species would show permanent hearing loss (often referred to as permanent threshold shift [PTS]). In contrast, temporary threshold shift (TTS), a short-term reduction in hearing sensitivity caused by exposure to intense sound, has been found in a number of species. After termination of the sound causing TTS, normal hearing ability may return over a period that may range from minutes to days depending on the intensity and duration of exposure. During a period of TTS, survival of the animals may be at risk. The effects and significance of different levels of TTS on free-living fishes have not been examined so far. There is evidence that, given the same type and duration of sound exposure, a much louder sound will be required to produce TTS in fish that do not hear well compared with fish that are more sensitive to sounds (see Chapter 132 by Smith for a discussion of TTS in fish). Physical effects such as TTS are likely to be governed largely by the transient characteristics of sounds (e.g., rise time, peak pressure, and signal duration) and influenced also by the duration of exposure.

Currently, no criteria have been set for damage to the auditory system of fishes, although recent data show that the onset of damage to sensory cells of the ear, a likely harbinger of hearing loss, occurs at SELs substantially higher than those that produce the onset of other physiological effects (Casper et al. 2013). There are substantial reasons for thinking that fish can be grouped into “types” that share hearing characteristics based on the presence or absence of a swim bladder. Many lacking swim bladders and some with swim bladders unconnected to the ear are sensitive only to particle motion and respond to only a narrow band of frequencies. Fishes with swim bladders that are close to the ear or intimately connected to the ear are sensitive to both particle motion and sound pressure and show a more extended frequency range.

6.3 Changes in Behavior

There have been very few studies of the behavior of wild free-swimming fishes in response to sound. Decreases in the catches of fish exposed to seismic surveys have been reported. Startle responses and changes in the movement patterns of fish have been observed. Direct observations of fish schools with sonar have shown fish diving and schools breaking up as a result of sound exposure (reviewed by Normandeau Associates 2012).

The National Marine Fisheries Service in the United States has used 150 dB re 1 μPa rms as a criterion for behavioral effects on protected species but without adducing data to support this choice and without taking into consideration differences in sound detection abilities and behavior of different species. More recently, Nedwell et al. (2007) suggested that strong avoidance responses by fish start at ~90 dB above the dB_{ht}(*Species*) thresholds of fish. Although this concept takes into consideration the hearing characteristics of individual species, the allocation of the $\mathrm{dB}_{\mathrm{ht}}$ metric is often open to doubt for reasons discussed earlier. Moreover, the assumption that strong avoidance occurs at a particular level above the $\mathrm{dB}_{\mathrm{ht}}(Species)$ requires experimental confirmation. A number of factors are likely to affect behavioral responses, including any prior experience and the similarity of the sound to biologically important signals. Indeed, making a general assumption that all (or even many) of the 32,000 species of fish respond to sound stimuli in a similar manner at a particular relative level is not, in our view, at all realistic.

Indications are that, certainly for behavioral responses, the detailed context of an animal's behavior, the environment, and immediate ecological imperatives may play important roles (Ellison et al. 2012). It is perhaps naive to seek single values of particular metrics to define a particular level of response.

Regulatory agencies have tended to address only the acute effects of sound on hearing and behavior. Chronic exposure to low- and moderate-amplitude sounds that last for long periods may not lead to mortality or injury, but any reduction in fitness may lead to increased predation, decreased reproductive potential, or other effects. Chronic exposure may, for example, cause a rise in the level of stress hormones, with long-term effects on the fitness and ability of the animal to survive.

6.4 Masking

Sounds of biological significance are produced by fishes and are often used for communication of reproductive state, location, presence of predators or competitors, or finding other members of the same species. Many other sounds of natural origin may also be important to fishes, including sounds made by prey, predators, and natural features in the soundscape. Sounds from both biological and physical sources may be important for fish orientation, navigation, and habitat selection. In the presence of man-made sound and other noise, there may be impairment of the ability of fishes to detect biologically relevant sound signals (see Chapter 28 by Dooling and Blumenrath). Background levels of noise in the sea are changing as a result of the imposition of man-made sounds, with unknown effects on the ability of animals to detect sounds and communicate with one another.

Currently, little is known about the masking effects of man-made sounds, and criteria for masking have yet to be developed. However, masking by man-made sounds may have important short- and long-term effect on the behavior and well-being of fishes.

7 Conclusions

It is critical for regulators to have knowledge of the levels of sounds that may harm fishes as well as levels that have few or no consequences. However, the setting of recommended sound levels or sound exposure criteria for injury, damage to the auditory system, or behavioral responses has long been controversial, largely because of a shortage of data. In this paper, we have set out some of the levels that have been suggested and have emphasized their strengths and weaknesses.

In 2004, the National Oceanic and Atmospheric Administration (NOAA) convened a panel to prepare sound exposure criteria for fishes and turtles. That working group has gathered and reviewed papers from both the peer-reviewed and gray literature on the exposure of fish and sea turtles to various sound sources. It is setting out broadly applicable sound exposure criteria to serve as guidelines for fishes and sea turtles across the complete range of taxa and sound types, considering a range of impacts. The working group expects to publish its report in 2014.

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Chapter 52
Calibration and Characterization of Autonomous Recorders Used in the Measurement of Underwater Noise

Gary Hayman, Stephen Robinson, and Paul Lepper

Abstract The use of autonomous recorders is motivated by the need to monitor underwater noise, such as in response to the requirements of the European Union Marine Strategy Framework Directive. The performance of these systems is a crucial factor governing the quality of the measured data, providing traceability for future underwater noise-monitoring programs aimed at the protection of the marine environment from anthropogenic noise. In this paper, a discussion is presented of measurement methodologies for the key acoustic performance characteristics of the recorders, including self-noise, dynamic range, and the absolute sensitivity as a function of frequency of the hydrophone and recorder system.

Keywords Calibration • Noise measurement

1 Introduction

As a consequence of the recognition of the potential damage that can be caused to the marine environment due to noise from anthropogenic activity, there is now a greater demand for measurements of noise in the ocean and coastal waters. This has led to a proliferation of autonomous underwater recorders appearing on the market over recent years. Where these devices are used for tasks requiring no absolute measurement, such as monitoring the presence of marine mammals, knowledge of the sensitivity of the system may not be required. However, for measurements of

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absolute levels of ambient or man-made noise, it is vital that the performance of the system, in terms of sensitivity, self-noise, and dynamic range, is known. Although the various methods for calibrating hydrophones are well documented (International Electrotechnical Commission [IEC] 2006; American National Standards Institute/Acoustical Society of America 2012), there is currently no standardization of the methods used to characterize autonomous recorders.

The UK National Physical Laboratory (NPL) has a government-funded project to look at calibration techniques for autonomous acoustic recorders. This paper summarizes the issues specific to the performance characterization of such devices and the possible methodologies to be investigated during the project.

2 Issues

An autonomous recorder typically consists of three stages: hydrophone, preamplifier, and analog-to-digital (A/D) converter. When calibrating such a device, the sensitivity of the complete system needs to be determined. In the calibration of hydrophones, the electrical signal produced by the device in response to the acoustic pressure can be measured directly. Typically, this is not the case with an autonomous recorder where the electrical signal is digitized and saved, usually in WAV file format, to onboard storage media for later analysis. The output of such a system is in digital counts, and to determine the sensitivity in units commonly used for hydrophones, i.e., volts/pascal (V/Pa) or decibels re 1 V/μPa, the full-scale range of the A/D converter needs to be known to translate the levels in the WAV file into actual voltages.

The overall sensitivity of an autonomous recorder can usually be changed by adjusting the gain of the preamplifier stage and needs to be set at a level appropriate for the type of signals to be measured. If the recorder is to be used for the measurement of low-level signals, such as ambient noise or distant sources, the sensitivity needs to be high enough to avoid poor signal-to-noise. If loud sources of noise are present, too high a sensitivity can lead to problems such as saturation, nonlinearity, and clipping.

The frequency response of the recorder needs to be high enough to faithfully record all the frequency components present. A higher sample rate will mean greater data storage requirements and can have an impact on the length of deployment of the system. In general, a flat response is desirable because resonances can lead to distortion of the signal.

Where an autonomous recorder is used to measure both low-level and high-amplitude signals, the dynamic range of the system becomes a particularly important consideration. This is generally determined by the maximum level at saturation and the noise floor and is also affected by the resolution of the A/D converter and any nonlinearity in the hydrophone and system. The presence of any nonlinearity will need to be known and fully characterized if the recorder is to be used to measure the absolute levels.

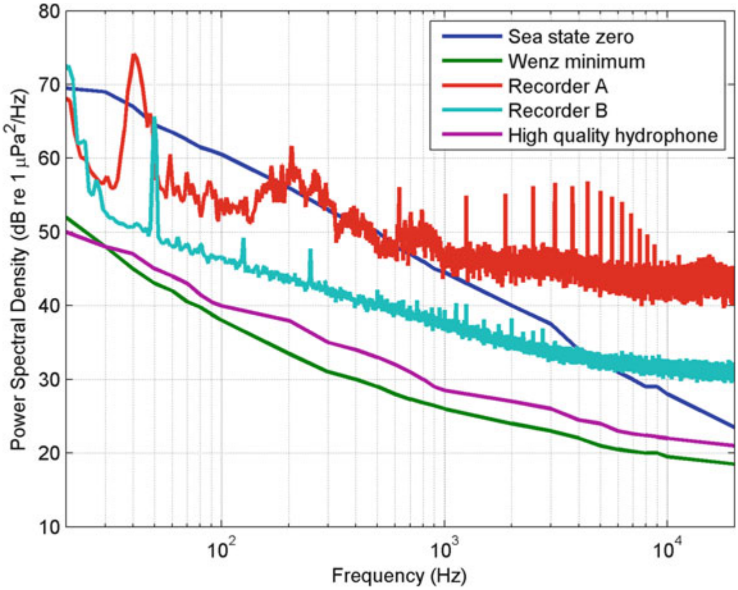

Fig. 52.1 Noise floor of three commercially available measurement systems compared with sea state 0 and Wenz minimum levels

An important performance characteristic of autonomous recorders, which is often ignored, is the noise floor. This is determined by the self-noise of the various components of the system and limits the lowest signal that can be measured by the recorder. Figure 52.1 shows the noise performance of three commercially available systems compared with both sea state 0 and Wenz minimum levels. It can be seen that some of the devices shown would not be suitable for use in the measurement of very low level ambient noise.

For the majority of measurements made in the marine environment using autonomous recorders, it is desirable that the response of the device should be omnidirectional. The design of many of the recorders on the market today is such that the hydrophone is mounted either directly to the recorder body or close to it on a very short cable. The recorder body is typically an air-filled cylinder that can scatter the acoustic signal and cause perturbation of the response at kilohertz frequencies. This can be a significant problem when using a recorder with a design to measure sound from a particular direction. For measurements such as ambient noise, where the noise is assumed to be incident from all directions equally, a certain degree of averaging of the measured signal with the incident angle will occur. Ideally, for the measurement of ambient noise, the diffuse field response of the recorder may be required. Where the recorder is being used to measure noise in broad frequency bands (for example, in third-octave bands), the appropriate sensitivity for that band is an average over the frequency band. At kilohertz frequencies, where the sensitivity is not constant and the recorder is not omnidirectional, the determination of the correct sensitivity may not be straightforward.

3 Measurement Methodologies

3.1 Pistonphone

This is a relative calibration method where the sensitivity of a device is determined by comparison to a reference microphone (IEC 2006). The unknown hydrophone and microphone are inserted into an air-filled chamber and simultaneously exposed to the same acoustic pressure. It is a method that can only be used for low frequencies, typically around 25–315 Hz, where the sensitivity of a hydrophone is the same in air as in water. The upper frequency limit is determined by the size of the chamber in that its dimensions must be small enough in relation to the acoustic wavelength for the sound pressure to be regarded as constant throughout the chamber. When used to calibrate an autonomous recorder, the recorder hydrophone is mounted in the pistonphone coupler along with a calibrated reference microphone and subjected to single tonal signals over the required frequency range. While the signals are being generated, the microphone output is monitored and the recorder is set to record the entire frequency sweep. After the completion of the sweep, the recorded WAV files are analyzed and the peak-to-peak voltage levels at each frequency are determined by applying the relevant scaling factor. From the recorded voltages and the sound pressure in the pistonphone coupler (measured by the reference microphone), the sensitivity of the system at each frequency can be calculated.

3.2 Open-Water Measurements

A free-field calibration requires a facility that has a large enough volume of water that free-field conditions may be approximated by ensuring that the reflections from the medium boundaries do not affect the measurements (typically, this is achieved through time gating of the acoustic signals). An example is the NPL open-water facility, which is a fully instrumented floating laboratory situated on a 20–m-deep freshwater reservoir. This facility has calibrated projectors and hydrophones that may be used to test the autonomous recorders up to high kilohertz frequencies. The devices are mounted at a depth of ~5 m or so by using a combination of tone-burst signals and windowing techniques; boundary reflections are gated out, whereas sound scattered from the body of the device is included in the analysis to investigate the effects of interference from the recorder body. By monitoring the drive voltage into the projector and knowing its transmitting voltage response and the device separation, the sensitivity of the autonomous recorder system can be determined from analysis of the waveform files recorded during the measurements. The mounting carriages at the facility also have a rotational capability that allows measurement of the directional response of the recorder. By making multiple measurements with the recorder mounted in different orientations, it is possible to build up a picture of the 3-dimensional directional response of the unit. This enables the effect of scattering from the recorder body on the omnidirectional nature of the hydrophone to be quantified.

3.3 Self-Noise

To measure the self-noise of an autonomous recorder and hydrophone, the system is placed in an acoustically isolated room that provides no external acoustic stimulus and the device is set to record for a period of a few minutes. The device is typically battery operated and isolated electrically from the mains supply in the laboratory, but if needed, measures may be taken to isolate the system under test from any electrical pickup from the surrounding environment. It is not uncommon for systems to pick up radiated electrical signals from the circuitry within the recorder, but this is part of the self-noise of the system being measured. At NPL, the recorded waveforms are analyzed using in-house software written in the MATLAB programming language, which uses the previously measured system sensitivity to determine the power spectral density and/or third-octave band power levels over the measured frequency range.

Acknowledgments We acknowledge the support of the National Measurement Office (NMO) of the UK Department for Business, Innovation and Skills, which is funding this work as part of the National Physical Laboratory (NPL) Acoustical Metrology Programme.

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Chapter 53
Intrinsic Directional Information of Ground Roll Waves

Richard A. Hazelwood and Patrick C. Macey

Abstract Ground roll waves traveling across the seabed provide extra information, their direction of rotation, compared with plane waves in fluids or solids. Idealized Rayleigh waves are "retrograde" in that their horizontal particle motion opposes the direction of travel of the wave when the interface is raised. A single point measurement near the seabed can determine this rotation. In water, there are associated evanescent pressure waves that are largely confined to the bottom, likely to affect fish and other creatures near the seabed during pile driving. The directional information may prove key to the lifestyle of such creatures.

Keywords Piling noise • Evanescent • Ambiguity • Directionality

1 Introduction: The Ambiguities Created in Direction-Finding Systems

Concern continues about the potential effects the sounds produced by piling driving may have on fish. As discussed at the Cork conference (Hazelwood 2012), there will also be seabed vibrations induced by the piling impacts, which are transmitted across the seabed as ground roll waves. Additional work since then has involved measurement of sediment motion near a test pile at Kinderdijk in the Rhine delta and significant extension of the finite-element analysis (FEA). The motion of the sediment will also move the water near the seabed. For the conditions modeled, this is largely confined to the bottom 1 m of water.

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At their low frequencies, which correspond to the sensitivities of many fish without swim bladders, the “180° ambiguity” reviewed by Rogers and Zeddies (2008) can be overcome by sensing the particle motion, specifically the relationship between the horizontal and vertical components of this motion.

There is a quadrature phase shift between these signals as sensed by a triaxis accelerometer or equivalent system. A phase analysis is thus required, but many current theories of fish awareness already invoke such signal-processing capability. Electronic direction-finding systems also use a phase analysis and often need to resolve ambiguities that can occur due to the sensor array limitations.

2 Nature of the Ground Roll Waves

Figure 53.1 shows a schematic wave in an elastic solid under a vacuum as described by Lord Rayleigh in 1887. His analytic mathematical solution applies to an infinite body, a “half space.” The travel direction of the wave is shown, but the particles follow a closed path, usually elliptical. An important feature of this idealized model is that there is no dispersion in that all frequencies travel at the same speed so that an impulsive waveform retains its original shape.

This simple response changes for more realistic models. A layered seabed might include a hard rock layer that reflects energy. The travel speed will then depend on the frequency and depth of the hard layer. The term “dispersion” describes the consequent changes in waveforms. Although very different in some respects, the “rolling” ocean waves demonstrate this feature well. The typical chaos of a storm occurs as the different wavelengths travel at different speeds. However, these are fluid gravity waves rather than elastic solid waves.

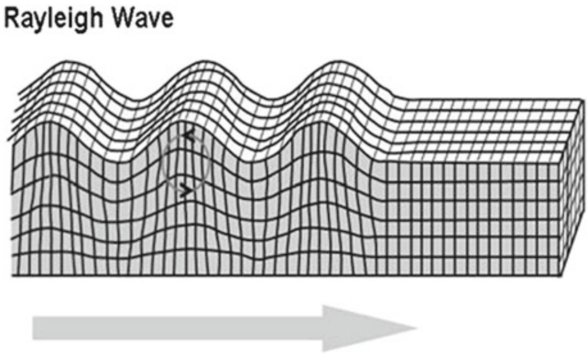

Fig. 53.1 Finite-element analysis diagram showing the deformation in ground roll. The schematic wave is in an elastic solid under a vacuum, as described by Lord Rayleigh in 1887. *Arrow*, travel direction of the wave, but the particles follow a closed path, usually elliptical. An important feature of this idealized model is that there is no dispersion in that all frequencies travel at the same speed. From Wikipedia

Although conditions in a shallow sea involve both fluid and solid waves, the wavelets studied here are primarily controlled by the solid waves. the general term "ground roll" is used in seismology (Yilmaz 1987) to indicate rolling motion rather than the linear "to-and-fro" motion seen in plane waves. "Stoneley" and "Scholte" waves are more narrowly defined (Jensen et al. 2000) but also show this rolling motion.

The underwater sound waves most studied are fluid pressure waves, often idealized as plane waves, with no reverberation. Energy then travels in one direction, orthogonal to this plane. Oscillatory particle motion then occurs along the same direction.

The sinusoidal velocity waveform is calculated by dividing the pressure waveform by the fluid-specific impedance, the product of the wave speed, and the density of the medium. It is only when there is significant deviation from the plane wave case that the particle velocity data provide any new information. This occurs near interfaces, where the situation can be complex, with energy traveling in many directions. The waves described here are, in some senses, simpler in that energy transport is always radial.

Although it is the elastic energy of the ground roll that primarily controls the waveform, the motion creates evanescent pressure waves in the nearby fluid. The magnitude of these pressure waveforms diminishes with the height above the seabed. For the low frequencies and very low speeds seen within saturated sediments, no energy is then radiated either up or down. There will be thermal losses (absorption) and cylindrical spreading losses but no energy escapes so that the propagation may be significant to ranges over 1 km. Explosion-generated ground roll waves have been measured out to ranges of over 2 km (Schmalfeldt and Rauch 1983), but these were of lower frequency than those seen at Kinderdijk in 2010 (Jansen et al. 2011).

3 Measurements

As reported recently in Corfu (Hazelwood and Macey 2013), the saturated sediments at Kinderdijk only transmitted energy in highly restricted ways. The sharp impact energy radiated into the water surrounding the pile differs from the nature of the ground roll in many ways.

Figure 53.2 shows the effects of two piling blows spaced by 1.6 s. Shortly after the acceleration measured within the pile and its rapid decay occurred, compression waves arrived at the geophones that had the sensitivity to show a similar rapid decay. Much later, the ground roll arrived, here measured by the geophone array discussed in Cork. Measurements were made at two ranges, 66 m as shown in Fig. 53.2 and 11 m. These later geophone signals provided a calibrated velocity response at 20 V/(m/s) appropriate for the low frequencies (<100 Hz) of the ground roll waves. They were seen to be restricted in bandwidth, with energy traveling at ~100 m/s but with typical oscillatory particle velocity components of a few millimeters per second.

The ground is seen to strongly filter the energy provided by the piling blow, accentuating the low-frequency ground roll, clearly visible in Fig. 53.2 for the quieter conditions after the higher frequencies have passed by. Recent propagation modeling using wave number integration (Jensen et al. 2000) techniques has confirmed this tendency for the layered seabed as modeled.

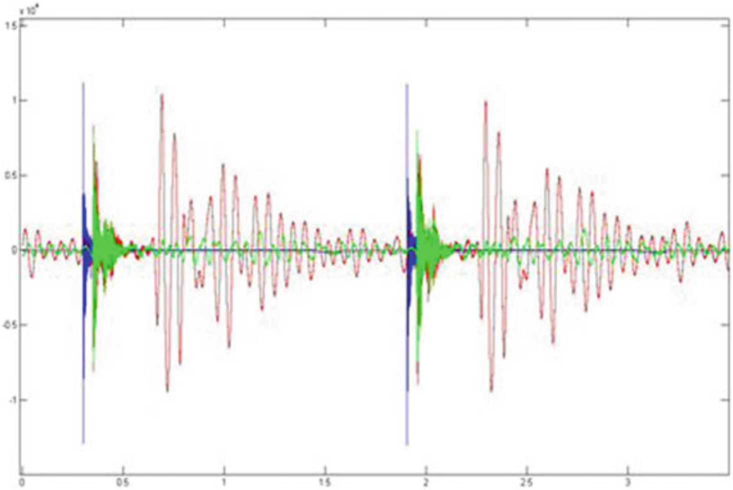

Fig. 53.2 Multisensory plot showing geophone and accelerometer responses. The effects of two piling blows were spaced by 1.6 s. *Blue trace*, acceleration measured within the pile and its rapid decay. Shortly thereafter, compression waves arrive at the geophones (*green trace*) that have the sensitivity to show a similar rapid decay. Much later the ground roll arrives, measured by the geophone array. Measurements were made at two ranges, 66 (shown) and 11 m. These later geophone signals provide a calibrated velocity response appropriate for the low frequencies of the ground roll waves

4 FEA Modeling

As discussed in Cork, there are many benefits in modeling, which allows analysis of simplified conditions while replicating the important physical characteristics of the measured waves.

The FEA model shown in Fig. 53.2 is for a shallow sea, 16 m deep. The shape of the remarkably short and simple wavelet is controlled mainly by the sediment data (an approximate fit to data from Hamilton 1980), but the modeled impulse has also been adjusted to simplify the display. In real conditions, this wavelet is likely to occur as part of a more complex field but here provides a simple model for discussion based on real data.

The FEA provides a time sequence at node 700 and also at node 8,394, which is colocated but represents the water pressure field in Fig. 53.3. This allows the pressure in the water to be compared with the acceleration of the seabed and shows the mass loading to be ~600 kg/m^2 for this model. The same wavelet shape is then seen. Whereas acoustic plane waves provide a simple linkage between the pressure and the water particle velocity, it is the acceleration of the ground roll that drives the pressures of these evanescent water waves, a different phase relationship (Hazelwood and Macey 2013).

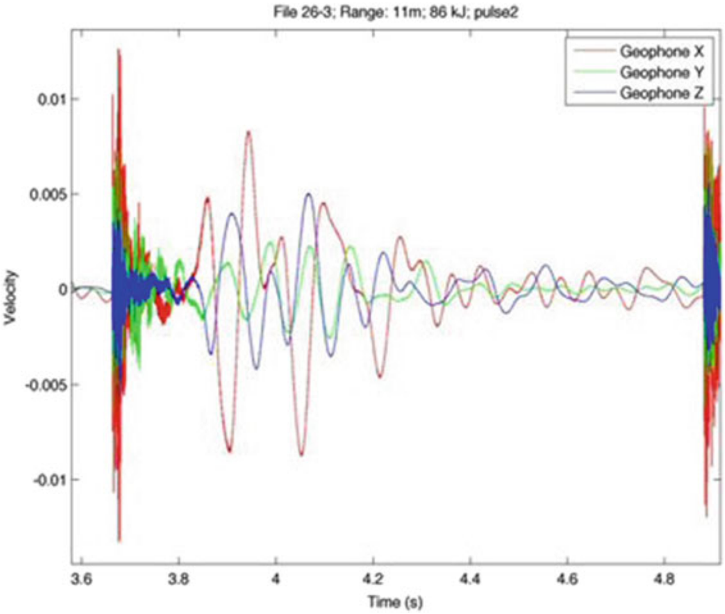

Fig. 53.3 Two-dimensional slice through an axisymmetric finite-element analysis (FEA) model showing pressures and displacements. Note the nodal points 900, 908, and 916 extending from the seabed to the surface. There is little sound pressure (*green*) except the intense localized pressure at the seabed (>2 kPa) generated by a 1-MN peak force impulse at the origin. This view is centered at these nodes, which are 32 m from the origin (not shown) to the left. Node 700 is at a radius of 64 m. The snapshot is of time step 640 at 0.32 s after the start of the impulse. This transient analysis produces animated sequences that show the waveform metamorphosis. The sediment as shown (*blue*) indicates a lack of deformation from rest. The displacement magnitude extends to just over 0.2 mm in this case. The deformation as shown is much exaggerated for clarity and is combined with a white gap separating the water and solid fields

5 Resolving the Ambiguity

An intrinsic difficulty in direction finding has been long discussed and is known as the 180° ambiguity. This occurs for small creatures detecting sound at low frequencies. The wavelength of the sound (plane waves) is then long. At 150 Hz, the wavelength is 10 m, and it is not possible to use the phase gradient for direction finding. The ability of fish, even those without swim bladders, to sense the particle motion using their otolith structures allows the "line of bearing" (e.g., southwest to northeast) to be determined but there is still a crucial directional ambiguity for a sinusoidal wave.

This problem is resolved by ground roll waves. To avoid uncertainties with biological detail this has been considered as a physics problem. One of us (R. A. Hazelwood) spent some years on means to overcome ambiguities created by a shipborne direction-finding sonar, a phased hydrophone array. For this related problem, we need a triaxial accelerometer with signal analysis to assess the direction of the "roll." For the wavelet as modeled, with its retrograde motion, the wave direction opposes the horizontal motion when the vertical displacement is maximal. A typical otolith structure of, e.g., a plaice seems adequate for a similar procedure to be conducted by fish. For any species that needs to hunt, the resolution of the ambiguity becomes even more important and this mechanism would seem beneficial for crabs as an example.

6 Testing the Sensitivity to Ground Roll

The nature of these evanescent waves can be used to construct a relatively simple test environment for small creatures using a whole body motion. The testing of human sensitivity to low-frequency vibration often considers whole body motion. An aquatic creature could be enclosed by an oxygenated water tank designed to behave as a substantially rigid entity at these frequencies. It will be necessary to carefully isolate the foundations from the all-pervasive ground roll of the environment using a soft suspension. Achieving a good replica phased motion may require some careful attention to detail.

7 Conclusions

There is some prospect of these studies leading to an area of underwater biological research that does not seem to have received much attention to date. Ground roll waves are seen as a nuisance to seismologists, and military research appears to have been concluded without the discovery of any significant application of use to humans. However, other creatures may have a different agenda.

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Chapter 54
A Permanent Soundscape Monitoring System for the Care of Animals in Aquaria

Kathy Heise, Harald Yurk, Chad Nordstrom, and Lance Barrett-Lennard

Abstract Sound pressure levels in facilities that house acoustically sensitive animals should be monitored on a regular basis as a standard component of animal care. Monitoring of noise levels in the pools housing *Lagenorhynchus obliquidens* (Pacific white-sided dolphins) at the Vancouver Aquarium during regular operations revealed average sound pressure levels (SPLs) across all frequency bins of 91.9 (range 87.0–104.5) dB re 1 µPa Root Mean Square (RMS). Sustained pressure levels were highest during cleaning, where ambient noise levels increased approximately 25 dB re 1 µPa RMS.

Keywords Underwater noise • Sound monitoring • Aquariums • Aquaculture • Dolphins • Animal care

1 Introduction

For captive aquatic animals, noise is ubiquitous. It is primarily due to the machinery (pumps, filters, skimmers etc.) that is used to maintain water quality. O'Neal (1998) found that sound pressure levels were up to 25 dB re 1 µPa (20 Hz to 6.4 kHz) louder in exhibits at the Monterey Bay Aquarium than in the inner and outer offshore environments they were simulating. Noise can be exacerbated by hard reflective surfaces and the geometry of the exhibits. Similarly, in a survey of noise levels in aquaculture operations, mean broadband SPLs ranged from less than 100 to over 150 dB re 1 µPa RMS (Bart et al. 2001). Hobby aquariums can also be very noisy (Jemmott 2010).

The consequences of chronic high noise level exposures depend on the species. *Hippocampus erectus* (lined seahorses) raised for the aquarium trade showed significant behavioural and physiological responses to chronic noise (Anderson 2011). *Crangon crangon* (brown shrimp) showed significant declines in growth and reproduction rates, and higher metabolic and mortality rates when raised in

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increased noise (Lagardère 1982; Regnault and Lagardère 1983). *Onchorynchus mykiss* (rainbow trout) are hearing generalists and are not especially sensitive to noise (Wysocki et al. 2007; Davidson et al. 2009) whereas noise causes stress and hearing loss in *Carrasius auratus* (goldfish), which are hearing specialists (Smith et al. 2004). In *Cyprinodon variegatus* (sheepshead minnow) and *Fundulus similis* (longnose killifish) additional noise resulted in reduced egg viability and reduced larval growth rates (Banner and Hyatt 1973).

A long-term study of the echolocation abilities of captive *Lagenorhyncus obliquidens* (Pacific white-sided dolphins) at the Vancouver Aquarium Marine Science Center revealed significant variation in underwater ambient noise levels in the pools on a day to day basis. The raising and lowering of gates, rain, and the dolphin's activity level resulted in additional noise. Machinery noise levels were variable, most likely due to pumps turning on and off and possible equipment malfunctions. Extraneous underwater noise due to equipment requiring maintenance has been documented in 10% of merchant ships off of Santa Barbara (McKenna et al. 2012). When the Aquarium began an expansion project in 2012, concerns around the introduction of potential additional noise associated with construction into the habitat provided the impetus to install an alarmed continuous sound monitoring system.

2 The Monitoring System

At the aquarium, the dolphins are kept in the Wild Coast Exhibit, which contains approximately 4,000,000 L of salt water. The main pool is 40 m long, has a minimum width of 10 m and a maximum depth of 6.9 m. and an outer wall that is approximately 15 m at the closest from the area under construction. The dolphins can swim freely into an oval-shaped "medical" pool that has a maximum diameter of approximately 10 m and a water depth of 3 m through a 1.5 m wide opening. There are two meshed gates approximately 1 m wide and 0.5 m deep that separate the main pool and the medical pool from a large holding pool housing *Eumetopias jubatus* (Steller sea lions) and *Phoca vitulina* (harbor seals) (Fig. 54.1). Two calibrated hydrophones (C55 Cetacean Research Technology) are deployed within the exhibit, one at 3 m depth in the main pool, and the second at 2 m depth in the large holding pool (Fig. 54.1). These hydrophones have a flat frequency response between 0.020 to 44 kHz (±3 dB) and can be used to record sounds reliably up to 100 kHz. An integrated preamplifier supplies a signal gain of 20 dB which results in a nominal response of −165 dB re 1 V/μPa across the flat frequency range of the hydrophone. A dual-channel mobile digital recorder (Sound Technology MDR 500) digitizes incoming signals with a sample rate of 100 kHz and 0 dB gain. RMS SPLs are recorded continuously for the whole frequency spectrum (10 Hz to 50 kHz) and for 1/3 octave bands (between 500 Hz and 50 kHz).

If sound pressure levels exceed pre-determined time and amplitude thresholds in any of the 1/3 octave frequency-bins, alarms are sent out to husbandry and research staff via SMS text messaging and e-mail, enabling mitigation measures to be put in place.

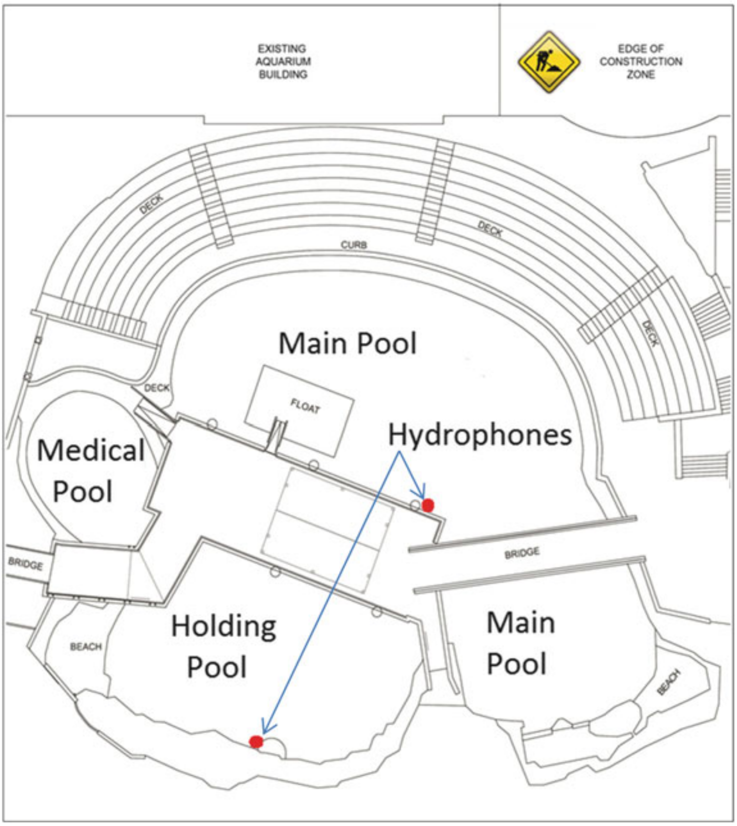

Fig. 54.1 General layout of the West Coast Exhibit at the Vancouver Aquarium, showing the location of the main pool, the medical pool and the holding pool. The locations of the two hydrophones are *circled*

The amount of time before an alarm is triggered is frequency-bin specific and is set manually, ranging from 0 to 30 s, and assumes that the dolphins can tolerate longer exposures at the outer ranges of their hearing sensitivity. Sounds are also live-streamed onto a network, enabling off-site monitoring of the habitat.

This technology has been useful in identifying unanticipated noise events associated with construction, as well as those that occur during day-to-day operations (e.g. cleaning, pumps requiring maintenance etc.). The average sound pressure level across all frequency bins during normal operations was 91.9 (range 87.0–104.5) dB re 1 μPa RMS. The most significant source of additional noise did not occur during construction or normal operations, but rather during weekly 30 min dive cleaning sessions, when the walls of the pools were being scrubbed using an Armada twin scrubber unit (www.poolscrubber.com). Cleaning increased noise levels by 25 dB, triggering the sound alarms (Fig. 54.2). During these cleaning sessions, the dolphins were moved to the medical pool.

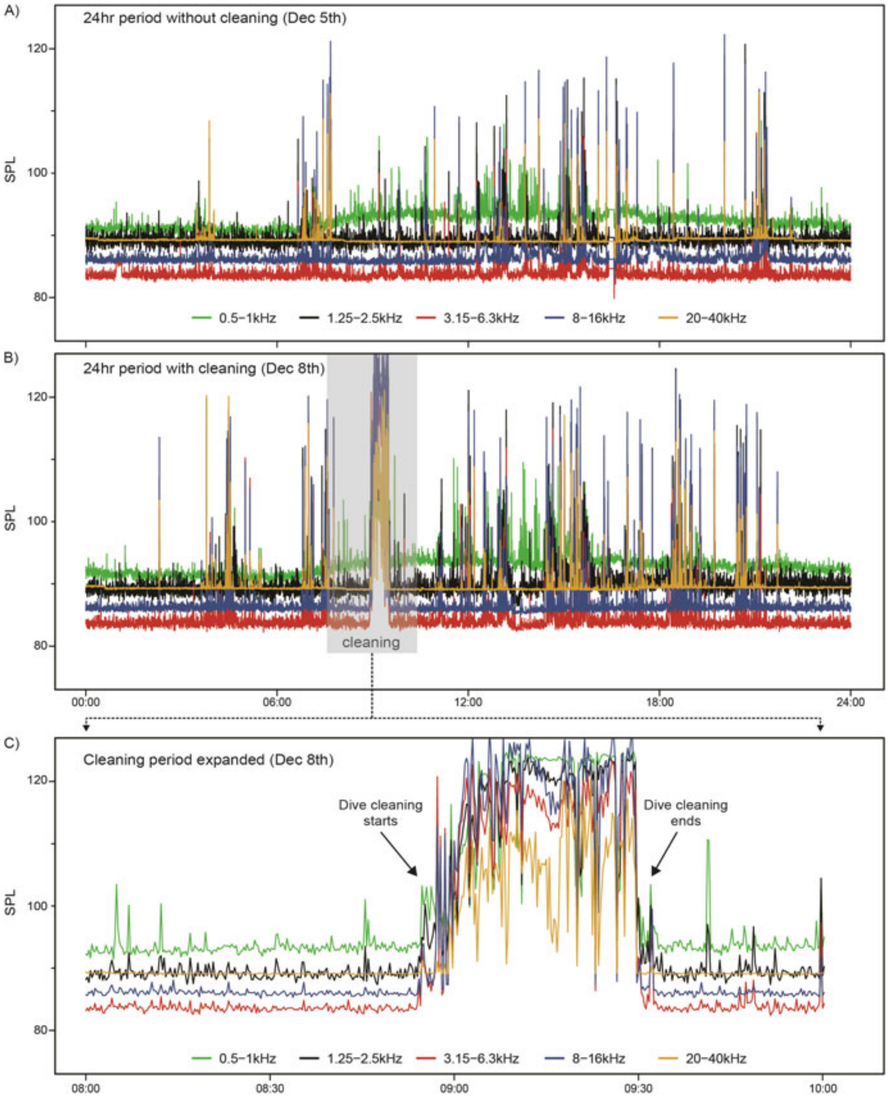

Fig. 54.2 Sound pressure levels in the main pool of the West Coast Exhibit at the Vancouver Aquarium during (**a**) a typical day, (**b**) a day that includes a habitat cleaning session and (**c**) a 30 min dive cleaning session

3 Conclusion

Monitoring sound pressure levels should become a routine component of water quality monitoring in facilities housing acoustically sensitive species. The levels can be highly variable within a holding system (this study) as well as between facilities. Sound pressure levels in nine public aquariums' seahorse exhibits ranged from

116 to 143 dB re 1 μPa RMS with a mean total power of 126 dB re 1 μPa RMS (10–980 Hz, Anderson 2013). Levels of 123.3 ± 1.0 dB re 1 μPa RMS are known to have impacts on their behaviour, physiology, growth and immune systems (Anderson 2011), thus the facilities with high noise levels may need to implement mitigation to improve the welfare of their animals. A temporary acoustic monitoring program at the Georgia Aquarium revealed that the pumps used to maintain water quality were noisiest below 1,000 Hz, and added ~10 dB up to 700 Hz over the hearing threshold of bottlenose dolphins, and ~20 dB re 1 μPa above 1,000 Hz (Scheifele et al. 2012).

Underwater noise is now a standard component of environmental water quality monitoring at the Vancouver Aquarium in the Wild Coast Exhibit, and will be extended to other exhibits in the near future. As our understanding of the impacts of noise increases, we hope that other facilities will begin to incorporate noise monitoring into their animal care protocols. Monitoring sound pressure levels has provided the additional benefit of increasing the general awareness of staff and the public around the issue of underwater noise.

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Chapter 55
Playback Experiments for Noise Exposure

Sophie Holles, Stephen D. Simpson, David Lecchini, and Andrew N. Radford

Abstract Playbacks are a useful tool for conducting well-controlled and replicated experiments on the effects of anthropogenic noise, particularly for repeated exposures. However, playbacks are unlikely to fully reproduce original sources of anthropogenic noise. Here we examined the sound pressure and particle acceleration of boat noise playbacks in a field experiment and reveal that although there remain recognized limitations, the signal-to-noise ratios of boat playbacks to ambient noise do not exceed those of a real boat. The experimental setup tested is therefore of value for use in experiments on the effects of repeated exposure of aquatic animals to boat noise.

Keywords Anthropogenic noise • Invertebrates • Particle acceleration • Acoustic pressure

1 Introduction

As international concern about the effects of underwater anthropogenic noise grows (Slabbekoorn et al. 2010; Tasker et al. 2010), the need for experimental data revealing the range and extent of impacts is becoming clearer. Given the logistical constraints involved with conducting in situ experiments near to the original sources of

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Table 55.1 Some of the issues involved with playbacks of anthropogenic noise in experimental setups

Issue	Reason	Effect
Frequency response of playback equipment	Frequency response of media player, amplification of signal, frequency response of loudspeaker	Small speakers are often unable to reproduce low frequencies accurately. Frequency content of playback may differ from original noise source
Constructive and destructive interference	Reflections from surface/bottom/edges	Some frequencies are louder, some are quieter. Frequency content of playback will differ from original noise source
Echoes	Reflections from surface/bottom/edges	Temporal content of signal will differ from original noise source
Near-field effects	Sound source (loudspeaker) often closer to experimental animals than the original sound source would be for logistical reasons	Particle motion and pressure could be out of phase, particle motion component of sound could be higher than that of original noise (dependent on frequency and distance to loudspeaker)
Cutoff frequency	Acoustic waves below established frequencies cannot travel when the water depth is too shallow	Low frequencies cannot propagate. Other types of waves may be involved

noise, it can be useful to employ playback experiments to test the effects of noise. However, playbacks do not fully replicate sound exposures that could be expected from real sound sources (Parvelescu 1967). Various issues that come into play include (but are not necessarily limited to) those discussed in Table 55.1.

The majority of marine macroorganisms are fish and invertebrates that, via commercial fisheries and other ecosystem services, have great ecological and socioeconomic value (Cheung et al. 2005). Although some species of fishes can detect sound pressure, all teleost fishes are able to use their otoliths to detect the particle motion component of sound (Bleckmann 2004). It is also becoming apparent that many invertebrates are able to detect the particle motion component of sound using statocysts (Mooney et al. 2010). Thus, although there are inherent limitations, attempts to improve the validity of playbacks should consider both acoustic pressure and particle motion. Here we used a field experiment in French Polynesia as a case study of an in situ field-based experimental setup. We present recordings of sound pressure and particle acceleration of original sound sources (outboard motorboats) and their playbacks in the experimental setup.

2 Recordings of Boats

Our study was conducted from the Insular Research Center and Environment Observatory (CRIOBE) Research Station, Moorea, French Polynesia. Boat traffic recordings were made during the day (on 4–5 November 2010) at a depth of 2 m in a deep bay in the lagoon on the east coast of Moorea using a hydrophone

(HiTech HTI-96-MIN with a built-in preamplifier, sensitivity −165 dB re 1 V/μPa, frequency range 2 Hz to 30 kHz, High Tech, Inc., Gulfport, MS) and a solid-state recorder (Edirol R-09HR 16-bit recorder, sampling rate 44.1 kHz, Roland Systems Group, Bellingham, WA). The recorder was fully calibrated using pure sine wave signals generated in SAS Lab (Avisoft), played on an MP3 player, and measured in-line with an oscilloscope. Thirty-six recordings of passes made by two typical outboard motorboats with 25-hp Yamaha engines were made; only 1 boat was used per recording. Boats started 50 m from the hydrophone and drove past in a straight line for 100 m, passing the hydrophone at a closest distance of 20 m. Boats were driven at one of three speeds: slow, medium, or fast. Each recording containing a boat pass lasted 45 s. Twelve 1- to 10-min ambient-noise recordings (without boats) were also made on location each day.

Pressure and particle accelerations of the same boats were recorded concurrently during the daytime (on 4–5 January 2013) at a depth of 2 m in a bay where the water depth was 5 m in the lagoon on the north coast of Moorea using the same hydrophone setup as above and an M201 acclerometer, (sensitivity, 0–3 kHz, GeoSpectrum Technologies, Dartmouth, NS, Canada; recorded on a laptop via a calibrated USB soundcard, MAYA44, ESI Audiotechnik GmbH, Leonberg, Germany; sampling rate 44.1 kHz).

3 Playbacks

Two sites that were similar in depth, water quality, prevailing currents, and proximity to the reef (>10 m) and nearest boat channel (>60 m) were used for playback experiments. The sites were 100 m apart and playbacks at one site could not be heard above the local ambient-noise levels from the other (verified with sound pressure and particle acceleration recordings made using the hydrophone and accelerometer detailed in Section 2).

Recordings were played using underwater loudspeakers (UW-30, frequency response 0.1–10 kHz, University Sound, Columbus, OH) fixed to the sandy bottom of a lagoon flat where the depth was 1.3–1.8 m. Each loudspeaker was powered by a 40-W amplifier (Kemo M034) powered by two 12-V batteries connected in parallel. Playbacks were played using MP3 players (Sansa Clip+, SanDisk, Milpitas, CA) that were on constant charge via a 5-V USB cable connected by a transformer to a separate 12-V battery. The playback system was fixed underwater in a waterproof case (Peli 1 200, Peli Products, Barcelona, Spain) inside a concrete block chained to the seafloor with a waterproof cable connecter (Standard Buccaneer, Bulgin, Cambridge, UK) for the speaker cable (underwater loudspeakers were situated on the seabed). Sound pressure and particle acceleration were measured 1 m from the speaker and compared with pressure and particle acceleration recordings of real boats and ambient noise from 4 to 5 January 2013. Five real-boat passes were compared with playback of five boat passes at each site along with 10-min of ambient noise and a random selection of 64-s samples of ambient-noise playbacks for 5 min.

4 Acoustics Analysis

Power spectral densities (PSDs) were calculated in MATLAB version 2010a. The data were calibrated according to the instrument sensitivities provided by manufacturers and split into 1-s windows that were Hamming filtered. A fast Fourier transform (FFT) was performed on each 1-s subsample to translate the data into the frequency domain. The FFT length was set equal to the sampling frequency of the recording (44.1 kHz) so that an absolute value for every 1 Hz could be obtained for each second of recording between 0 and 22.05 (the Nyquist frequency). These values were squared to obtain the PSD, multiplied by 2, and divided by 1.36 to correct for the noise power bandwidth. The mean, median, and 5th and 95th percentiles of all the 1-s values were taken at each frequency within each recording before multiplying by 10 $\log_{10}$ to convert the values into decibels re 1 $\mu Pa^2/Hz$ for sound pressure PSD levels and decibels re 1 $(\mu m/s^2)^2/Hz$ for particle acceleration PSD levels. The three axes (horizontal: *x*; perpendicular horizontal: *y*; vertical: *v*) of particle acceleration were examined separately.

5 Results

The *x*-axis of particle acceleration revealed the greatest difference between ambient noise at the playback site and boat playback levels; thus, for ease of presentation, this is the only axis shown in Figs. 55.1 and 55.2 (boat playback in the *y*- and *v*-axes

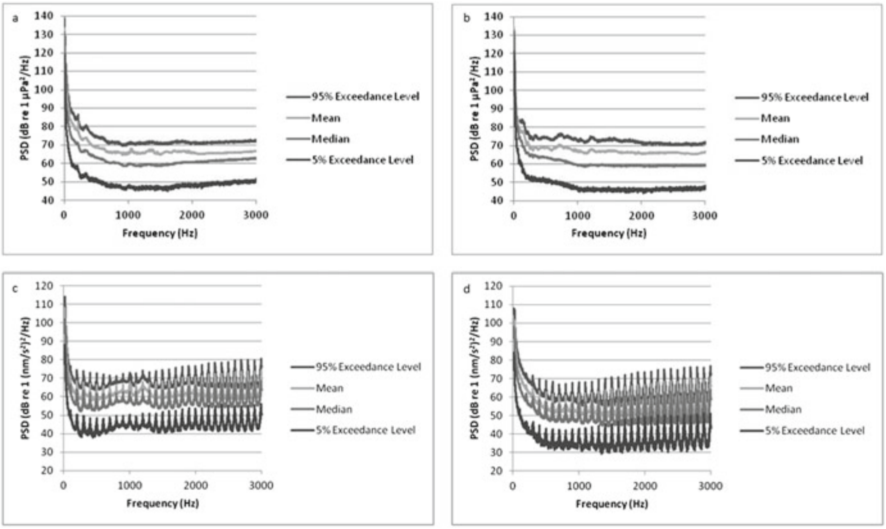

Fig. 1 Mean, median, and 5th and 95th percentile power spectral densities (PSDs) of 10-min ambient noise in pressure (**a** and **b**) and particle acceleration (**c** and **d**) at sites 1 and 2, respectively. Only one axis of particle acceleration is shown for clarity of presentation

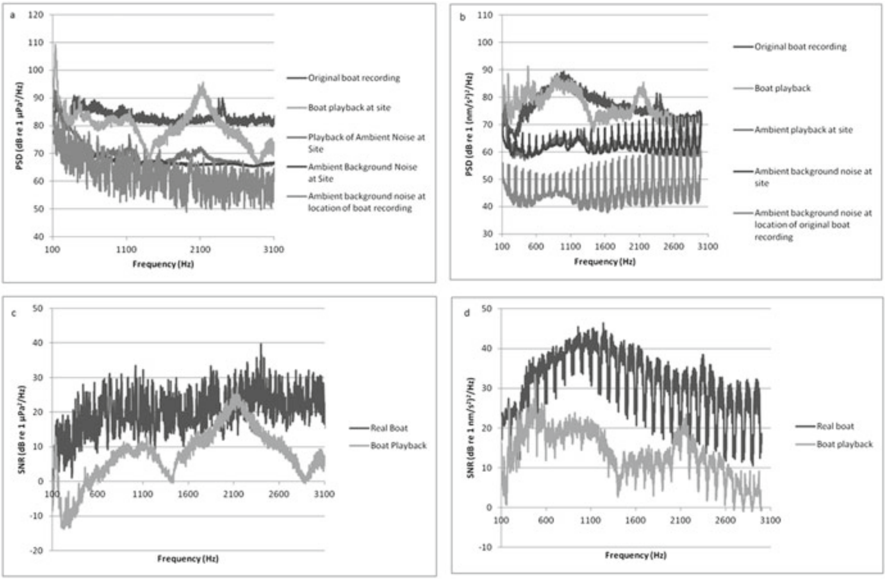

Fig. 55.2 PSDs (means) of five real boat passes, five playbacks of boat passes, 10-min ambient noise, and 5-min ambient-noise playback in pressure (**a**) and particle acceleration (**b**) at each site and signal-to-noise ratios (SNRs) of real boat and boat playback to ambient noise and ambient-noise playback, respectively, in sound pressure (**c**) and particle acceleration (**d**). Only one axis of particle acceleration is shown for clarity of presentation. Frequencies below 100 Hz are not shown here because our loudspeaker was unable to produce frequencies below 100 Hz

was a maximum of 17.8 dB above ambient noise at the playback site in any 1-Hz band, while in the *x*-axis, the maximum difference was 32.1 dB). The ambient-noise levels and variability at both experimental sites were similar to each other in terms of both pressure and particle acceleration (Fig. 55.1). PSDs of playbacks in comparison with the original recordings revealed that the sound pressure levels of boat playbacks were higher than those of real boats below 464 Hz and between 1,879 and 2,301 Hz. Particle acceleration levels of boat playbacks were higher than those for real boats below 598 Hz and between 1,995 and 2,205 Hz (Fig. 55.2a, b). However, the signal-to-noise ratio of a real boat to the ambient noise where the boat was recorded was not exceeded by that of boat playback to ambient-noise playback in terms of either sound pressure or acceleration (Fig. 55.2c, d). Our recordings of particle acceleration contained electrical noise with regular peaks every 100 Hz (Figs. 55.1c, d and 55.2c, d).

6 Applications

Previously, comments on running experiments in close proximity to loudspeakers had suggested that the particle motion component of sound would dominate the sound field at a magnitude that was unrealistic in relation to real exposure to anthropogenic noise sources. Our recordings from this particular setup suggest that for frequencies above 598 Hz, the particle acceleration of playbacks matched that of real boats more closely than the sound pressure. Although the particle acceleration at frequencies below 598 Hz does exceed that of a real boat driving at a distance between 10 and 50 m, the signal-to-noise ratio of a real boat to the ambient noise where it was recorded was greater than the signal-to-noise ratio of the boat playback compared with the ambient-noise playback. Although this is likely due to our choice of site having a louder ambient noise than the location where the boat was first recorded, the locations were representative of the habitats where our study species of choice for the experiments using these playbacks may be found. The experimental setup described here has been used to investigate the effects of repeated noise exposure on fish and sea hares (marine gastropod mollusks; Nedelec et al. 2014; Nedelec, Mills, Lecchini, Simpson, and Radford, in preparation). An ideal approach for future work will be to combine the use of playbacks with real noise exposures to confirm the validity of the use of a particular model species (see Chapter 129 by Simpson et al.).

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Chapter 56
Natural Variation in Stress Hormones, Comparisons Across Matrices, and Impacts Resulting from Induced Stress in the Bottlenose Dolphin

Dorian S. Houser, Cory D. Champagne, Daniel E. Crocker, Nicholas M. Kellar, John Cockrem, Tracy Romano, Rebecca K. Booth, and Samuel K. Wasser

Abstract Knowledge regarding stress hormones and how they vary in response to seasonality, gender, age, and reproductive status for any marine mammal is limited. Furthermore, stress hormones may be measured in more than one matrix (e.g., feces, blood, blubber), but the relationships between levels of a given hormone across these matrices are unknown, further complicating the interpretations of hormones measured in samples collected from wild animals. A study is underway to address these issues in a population of bottlenose dolphins trained for voluntary participation in sample collections from different matrices and across season and time of day.

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Keywords Cortisol • Aldosterone • Thyroid hormones • Catecholamines

1 Introduction

The last decade has seen an increase in the number of research efforts attempting to characterize the response of marine mammals to anthropogenic noise exposures. These responses have frequently been investigated using behavioral response studies under the assumption that the disruption of natural behaviors results in some cost to the animal whose behavior has been disrupted. The costs presumably scale with the behavior that is disturbed. Certainly, missed breeding and foraging opportunities can potentially be related to decreased fecundity or reduced energy acquisition and other altered behaviors might have energetic or fitness costs as well. However, the consequences of anthropogenic noise exposure can also occur at physiological levels that might not correlate with behavior, a process that is often referred to as the "stress response."

The concepts of stress and the stress response have evolved from the notions of homeostasis and the general adaptation syndrome (Cannon 1932; Selye 1936). There is no universally accepted definition of stress, and models of stress and the stress response are currently topics of debate (e.g., allostasis vs. the reactive scope mode; Romero et al. 2009; McEwen and Wingfield 2010). Nevertheless, the physiological response to an external or internal perturbation that enables an animal to respond to and recover from the perturbation can be loosely defined as a stress response. The stress response, which is beneficial to an animal over certain magnitudes and timescales, still results in costs to the organism, and remaining in a persistent stressed state can result in disease, reduced fecundity, decreased longevity, and physiological dysfunction.

The general adaptation syndrome is probably the most notable and well-characterized example of the stress response. In short, the general adaptation syndrome states that when an animal is affected by a stressor, the body produces glucocorticoids to prepare the animal for dealing with the stressor. Cortisol, the major glucocorticoid in many mammals, increases blood glucose, affects metabolism of fat and protein, and mediates inflammatory processes. Although cortisol is the most heavily studied of the stress hormones, it is now known that a suite of hormones can help an animal deal with both acute and chronic stressors. These include other glucocorticoids, the catecholamines (epinephrine and norepinephrine), thyroid hormones, and other neuroendocrine responses.

The stress response has received considerable attention in some biological systems, particularly as the field of conservation physiology has developed over the last couple of decades. However, the stress response is poorly understood in sound-exposed marine mammals and is limited by information on stress hormone variability as a function of age, gender, reproductive status, life history stage, and seasonality for nearly every species of marine mammal. This information is critical in interpreting stress hormone measurements obtained from wild marine mammals and made from various matrices (e.g., feces, blood, blubber), particularly because blubber and feces are more likely candidate matrices for collection from wild animals than is blood. Here, a current study is described in which baseline hormonal variation, relationships between hormone levels in different matrices, and the responsiveness of components of the stress response system are characterized in the bottlenose dolphin (*Tursiops truncatus*).

2 Methods

2.1 Season, Age, and Gender Effects

Thirty *T. truncatus* housed at the US Navy Marine Mammal Program were monitored for a year to characterize seasonal and demographic variations in the corticosteroids (cortisol and aldosterone), catecholamines (epinephrine and norepinephrine), and thyroid hormones and to determine the relationships between hormone levels measured across different matrices. Voluntary blood and fecal samples were collected biweekly through voluntary participation of the subjects. Blood samples were collected between 700 and 1,000 h. Monthly blubber biopsies were obtained from a subset of the subjects using a tissue biopsy punch. Serum and plasma hormones were processed by radioimmunoassay (RIA) or enzyme-linked immunosorbent assay (ELISA). Plasma catecholamines were processed in parallel with high-performance liquid chromatography (HPLC) as an external validation of RIA methods. Hormone metabolites were extracted from the blubber and fecal samples before processing with RIA.

2.2 Diurnal Variation

A current, year-long study is investigating diurnal variation in hormone levels. Sampling is performed as described in Section 2.1, but only ten animals are being utilized and samples are collected on a monthly basis. The study is methodologically different from the seasonal study in that voluntary blood samples are collected at three different times on the day of collection, at 700, 1,200, and 1,700 h. Fecal samples are collected the day after and 1 week after blood sampling.

2.3 Cortisol Feeding Study

A study was conducted with five *T. truncatus* that were fed cortisol every 6 h over a period of 4–5 days. Blood samples were taken on a daily basis and blubber biopsies were collected every 2 days to determine the relationships between blubber and serum cortisol levels and to characterize the biological half-life of cortisol.

2.4 Adrenocorticotropic Hormone Challenge

Adrenocorticotropic hormone (ACTH) challenges are currently being conducted to investigate the time course of hormone variability across matrices after an induced stress event and to determine immune system impacts resulting from persistently elevated cortisol. Subjects are given an intramuscular injection of ACTH slow-release gel and repeated blood samples are collected over a period of 5 days. Blubber samples are collected every 2 days and fecal samples are collected daily. All matrices will be processed as previously described to characterize activation of the hypothalamus-pituitary-adrenal (HPA) axis and to determine how the cascade of hormone variations is reflected in the different matrices.

2.5 Thyroid Hormone Challenge

Thyroid hormone challenges will be conducted to investigate the time course in hormone variation across matrices following an acute increase in thyroid hormones, which are key regulators of metabolism. Subjects will be given an intramuscular injection of either thyroid-stimulating hormone (TSH) or thyrotropin-releasing hormone (TRH). Blood samples will then be repeatedly collected over a period of 4 h while fecal samples will be collected opportunistically for a period of 96 h after the injection. All matrices will be processed as previously described to characterize activation of the hypothalamus–pituitary–thyroid (HPT) axis and to determine how the cascade of hormone fluctuations are reflected in the different matrices.

3 Results

Samples from the seasonal study and cortisol feeding study are currently being processed. The diurnal variation study and ACTH challenge study are currently underway. The thyroid hormone challenge study is slated to begin later this year. Because each of these studies is in a different stage of progress, only results from preliminary analyses are presented here.

Mixed models were used to evaluate variability across individuals in the seasonal study; an individual subject was included as a random effect to account for repeated sampling, and each hormone was used as a response variable. No significant differences were observed between the sexes for any of the hormones investigated to date ($P>0.05$ for ACTH, thyroid hormones, and catecholamines). However, several hormones showed significant seasonal variation ($P<0.05$ for epinephrine, norepinephrine, and thyroid hormones). ACTH and corticosteroid concentrations were markedly lower than those reported for wild-caught animals, but low levels were not due to adrenal exhaustion because certain veterinary procedures were observed to activate the HPA axis and increase both cortisol and aldosterone.

4 Discussion

The study described here is the largest and most comprehensive study of stress hormones in a cetacean; to date, over 1,000 individual serum and plasma samples have been collected representing males and females from 6 to 42 years of age. The results will provide comprehensive information on seasonal, diurnal, and demographic influences on hormone variability in *T. truncatus* as well as on the relationships between hormone levels and fluctuations in different matrices. It will provide a baseline to which measurements in wild dolphins and captive dolphins exposed to anthropogenic sound can be compared and will thus provide a context in which to determine how physiological responses to anthropogenic stressors, including acoustic stressors, might deleteriously impact marine mammals.

The preliminary analysis here suggests that the hormone values observed in *T. truncatus* under human care and collected under voluntary conditions are markedly lower than those reported for wild-caught animals. This suggests that free-ranging *T. truncatus* typically have higher concentrations of ACTH, aldosterone, and cortisol due to environmental factors or that handling disturbance in wild *T. truncatus* increased hormone concentrations before sample collection. Preliminary analyses further suggest that aldosterone production is an important aspect of the stress response in *T. truncatus*. Relative to terrestrial mammals, this may have greater implications for stress impacts on marine mammals because of their life in a hyperosmotic environment. As such, aldosterone should potentially be given the same level of consideration as a stress marker that cortisol has received, particularly because the two hormones share a synthetic pathway.

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Chapter 57
Risk Functions of Dolphins and Sea Lions Exposed to Sonar Signals

Dorian S. Houser, Steven W. Martin, and James J. Finneran

Abstract Acoustic dose-response functions have been recommended as a means of predicting behavioral impacts on marine mammals from anthropogenic noise exposure. Thirty bottlenose dolphins and fifteen sea lions participated in a controlled exposure study to explore dose-response relationships to the received level of a simulated sonar signal. Both species showed an increase in the probability of response and in the severity of response with increased received levels. Differences in species sensitivity were noted in habituation and the impact of age on responsiveness.

Keywords Dose response • Behavioral reaction • Sound • Noise

1 Introduction

Dose-response functions have been recommended as a means of exploring the relationships between received levels of anthropogenic sound and the behavioral reactions of exposed marine mammal species (Southall et al. 2007). Indeed, regulatory agencies within the United States have permitted and adopted a dose-response approach to estimating the degree to which marine mammals might be harassed (behaviorally disrupted) by the ocean acoustic activities of the US Navy (Department of the Navy 2008a, b, c). Although intuitive and beneficial to meeting the regulatory requirements of the United States, the information that exists on the relationship between sound exposure and marine mammal behavioral reactions is lacking. The current dose-response functions employed by the US Navy and National Marine

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Fisheries Service (NMFS) are based on a compilation of diverse data sources that mix species (mysticetes and odontocetes) and sound sources and that have varying degrees of uncertainty (i.e., some data collected under controlled conditions and some from observations of sonar incidents). Collectively, these data sources have been used to make two dose-response functions, one for mysticetes and one for all other marine mammals, with a few exceptions (e.g., harbor porpoise, beaked whale). Although the collective data used to derive the current dose-response functions leave much to be desired, the data were the best available at the time the functions were first developed.

There has been a surge in research activity in recent years to perform acoustic playback studies on wild marine mammals, in large part to collect data that might be used to better predict marine mammal responses to anthropogenic sound. Although wild marine mammals are the most desired for such studies, conducting playbacks in the wild is challenged by limited control over playback conditions, unknowns regarding animal context (e.g., the animal's current activity and motivational state, prior experience with a source, proximity factors, impacts of tag placement), and the potential impact of experimenter presence and proximity. An alternative approach to collecting dose-response data is to use animals under human care. The benefits to this approach are that a more consistent exposure context can be created across subjects, received levels can be more controlled, and historical and demographic information relevant to the response analysis can be obtained. The drawback to this approach is that the animals utilized are likely to have been under human care and stimulus control for considerable periods of time and their responses may not be representative of conspecifics in the wild. Thus, both approaches can be used to make positive contributions in determining dose-response relationships between behaviors and received sound level but both also have limitations that must be considered during analysis and interpretation.

An additional issue, and one that will require some prioritization by the scientific and regulatory communities, is that there are probably distinct differences in a species' sensitivity to sound. As observed in the response of avian species to urbanization, some species do well in the face of novelty and habitat encroachment while others do not. Certain species appear to have an intrinsic resistance or adaptability to a changing environmental landscape in either or both of acute and chronic perturbations. The same is likely true of marine mammal species, and there is probably a wide range of tolerances and robustness to environmental change. Thus, species that are of greater concern or that might be perceived as more sensitive to acoustic disturbance may be targeted for behavioral-response studies first or surrogate species with close phylogenetic and/or ecological linkages may be targeted for study in their stead. Nevertheless, it is apparent from the survey of available literature that differences in species responsiveness to acoustic disturbance remains largely undetermined at worst and only qualitatively addressed at best.

Here an acoustic exposure study that was conducted for the purpose of determining the dose-response relationship between the received sound level of a simulated midfrequency sonar signal and the behavioral response of two species of marine mammals is described. The study used marine mammals under human care, specifically the bottlenose dolphin (*Tursiops truncatus*) and the California sea lion

(*Zalophus californianus*). These species represent commonly occurring species in US Navy operational areas along the east and west coasts of the United States, respectively. The use of the two species also allowed for differences in the factors affecting species responsiveness to acute acoustic disturbance to be explored and the overall tolerance of each species to acoustic disturbance to be better characterized.

2 Methods

Thirty *T. truncatus* and fifteen *Z. californianus* maintained by the US Navy Marine Mammal Program participated in a controlled exposure study. The subjects were trained to leave a station (A) on cue by a trainer, travel to another station (B) and touch a paddle, and then return to the original station (A). The completion of this “ABA” task within a 30-s trial period resulted in the animal receiving a fixed fish reward equal to 1% of its daily allotment of fish. Once a subject attained 100% completion across a 10-trial block, the subject was asked to perform a 10-trial control session followed by a 10-trial sound exposure session.

All sessions were performed in a 9.1- × 18.3-m floating pen with an underwater sound projector placed 1 m behind station B. No sound exposure occurred during the control session. During the subsequent exposure session, each animal received an acoustic exposure at the midpoint of the enclosure on its initial path to station B. One exposure per trial was given. An acoustic exposure consisted of a 0.5-s upward frequency-modulated (FM) sweep (center frequency ~3,250 Hz) followed by a 0.5-s continuous wave (CW; ~3,450 Hz). Received sound pressure levels (SPLs) ranged from 115 to 185 dB re 1 μPa for *T. truncatus* and from 125 to 185 dB SPL for *Z. californianus*. The received SPL assigned to an animal was held constant throughout the exposure session. This design permitted five *T. truncatus* to be tested at each received level (115, 130, 145, 160, 175, and 185 dB SPL) and three *Z. californianus* to be tested at each received level (125, 140, 155, 170, and 185 dB SPL).

Sessions were video recorded and intercom and underwater recordings were mixed together with the video recordings to create audio/video (A/V) files with time-aligned acoustic and visual events. Behavioral responses anticipated to occur were identified before testing; however, several unanticipated behavioral responses were added to the list during the analysis. Behavioral responses were also assigned a severity score based on a previously proposed severity scale (Southall et al. 2007). Two scorers who were not involved with the study design or the testing of the animals were employed to score the A/V files for the occurrence of any behavioral reaction (one A/V file per session). Before scoring the A/V file, silence was inserted into the file at the point that the subject crossed the middle of the enclosure. This was performed to prevent the scorer from knowing via audible signals whether the trial was from a control or exposure session.

A canonical correlation analysis was used to determine relationships between the independent factors (age, trial number, and exposure level) and the behavioral responses. Reliable indicators of a behavioral response to the acoustic exposure, as demonstrated by the analysis, were then used in the creation of dose-response and dose-severity functions. The probability of a behavioral response across all subjects receiving the same SPL was compared with the received SPL for determining dose-response functions. Similarly, the maximum severity score from each individual was averaged across all individuals receiving the same SPL to determine the dose-severity functions.

3 Results

The results of the bottlenose *T. truncatus* study have recently been reported (Houser et al. 2013). Briefly, *T. truncatus* exposed to simulated sonar signals at levels ranging from 115 to 185 dB SPL showed a rapid habituation across the course of ten playback trials. Habituation occurred at levels ≤160 dB SPL and consisted of a reduction in the occurrence of mild responses. At received levels ≥175 dB SPL, responses were severe (e.g., behavioral abandonment) and no habituation occurred. In *T. truncatus*, the dose-response relationship was best described by an asymmetric relationship between the probability of a behavioral reaction and the received SPL, particularly when all trials were considered for the development of a single function (Fig. 57.1). Conversely, the relationship was adequately fit by a symmetrical function in the case of *Z. californianus*. Unlike *T. truncatus*, *Z. californianus* showed no habituation to repetitive exposures. However, age was a significant factor in the analysis, and young animals were more responsive at low received levels than were older animals. The removal of animals <2 years of age changed the shape of the dose-response function but had little impact on the dose-severity function.

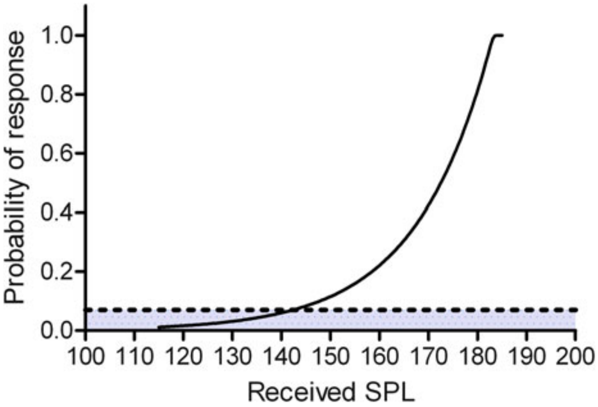

Fig. 57.1 Acoustic dose-response function for the bottlenose dolphin with a simulated midfrequency sonar signal as the acoustic stimulus. Relationship between the probability of a reaction and the received sound pressure level (SPL; in dB re 1 μPa) is for all trials combined, which washes out the habituation process. *Dashed line* and *shaded area*, probability of incorrectly classifying a behavior as a response to an acoustic exposure when no anthropogenic sound source is present. From Houser et al. (2013), with permission from Elsevier

4 Discussion

The relationship between an acoustic exposure and the probability and severity of a behavioral response will be affected by a number of factors. These include the amplitude and duration of the sound, the duty cycle of the source, the animal's prior experience with the source, the animal's motivation (e.g., feeding, mating, resting), the proximity of the source and any associated vessels, and inherent factors such as species or individual tolerances to novelty and perturbation. Given the number of factors involved, determining a relationship between any single factor and the received level of sound can be a challenging task because other factors may be uncontrolled or unknown. In this study, a test scenario was developed that was held constant for many of the aforementioned factors for all participating subjects representing two different species. Distinct differences in the responsiveness of *T. truncatus* and *Z. californianus* to the same exposure and under the same context were observed.

The habituation of *T. truncatus* to the repetitive simulated sonar exposures is not completely surprising because they are generally considered a robust species with a cosmopolitan distribution (Perrin et al. 2009). *Z. californianus* is also considered a robust species, but no habituation to repetitive signal exposure was observed over the course of the study. *Z. californianus* may have habituated over a longer time course, but for *T. truncatus*, a decision was quickly made that received signals below a certain level were either tolerable or nonthreatening. These findings speak to differences in species' tolerances and argue for treating the probability of response to an acoustic exposure for these two species according to their tolerance. Additional work should be conducted on species of interest because there are likely large differences in species' tolerances to acoustic disturbance, particularly in those that are more cryptic or prone to predation.

Age was a significant factor affecting the dose-response relationship in *Z. californianus* and a similar but more marginal relationship was found in *T. truncatus*. Across a number of species, young animals show a tendency to respond to novel or threatening stimuli at levels below which adults exhibit similar behaviors (Ramakrishnan and Coss 2000; Lea and Blumstein 2011). This may be due, in part, to increased predation vulnerability and uncertainty regarding acoustic indicators of a potential threat. In species that have varying distributions by age and gender, such as *Z. californianus*, this factor should be an important consideration to regulators because the age and gender distribution could affect the acoustic dose-response relationship and the potential to cause acoustic harassment.

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Chapter 58
Residency of Reef Fish During Pile Driving Within a Shallow Pierside Environment

Joseph D. Iafrate, Stephanie L. Watwood, Eric A. Reyier, Matthew Gilchrest, and Steven E. Crocker

Abstract The potential effects of pile driving on fish populations and commercial fisheries have received significant attention given the prevalence of construction occurring in coastal habitats throughout the world. In this study, we used acoustic telemetry to assess the movement and survival of free-ranging reef fish in Port Canaveral, FL, in response to 35 days of pile driving at an existing wharf complex. The site fidelity and behavior of 15 sheepshead (*Archosargus probatocephalus*) and 10 gray snapper (*Lutjanus griseus*) were determined before, during, and after pile driving. No obvious signs of mortality or injury to tagged fish were evident from the data. There was a significant decline in the residency index for mangrove snapper at the construction wharf after pile driving compared with the baseline, although this may be influenced by natural movements of this species in the study area rather than a direct response to pile driving.

Keywords Anthropogenic noise • Fish • Pile driving • Telemetry • Tagging

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1 Introduction

It has been shown that high-intensity sound sources such as pile driving are capable of inducing injury or hearing threshold shifts in fish at close range to the source (California Department of Transportation 2009; Halvorsen et al. 2011). Although it is expected that an intense source and its associated pressure waves would result in injury to a very small percentage of a population, behavioral changes can occur at greater distances from the source and therefore may affect a larger portion of a population by causing movement of the fish away from a feeding or breeding ground or changes in migratory or communicative behavior (Bridges 1997; Popper 2008; Slabbekoorn et al. 2010).

There is a lack of in-depth behavioral studies examining the effects of high-intensity sounds on fish in the wild (Popper 2008; Slabbekoorn et al. 2010; Normandeau Associates Inc. 2012). The most prominent studies thus far have explored the effects in enclosed environments where behavior cannot be confidently extrapolated to wild animals (Schwarz and Greer 1984; Jørgensen et al. 2005; Popper et al. 2007), the immediate behavioral responses of a single species cannot be investigated (Knudsen et al. 1992, 1994; Gearin et al. 2000), or direct behavioral observations of individual fish could not be included (Culik et al. 2001; Bolle et al. 2012).

In this study, the movement of free-ranging reef fish in Port Canaveral, FL, is documented through the use of acoustic telemetry in response to pile driving. Sheepshead (*Archosargus probatocephalus*) and gray snapper (*Lutjanus griseus*) were chosen as target species due to their abundance, their membership in diverse reef fish families (Sparidae and Lutjanidae), and known high site fidelity to hard-bottom habitats (Reyier et al. 2010). Underwater acoustic receivers were deployed within Port Canaveral to complement an existing array of compatible receivers spanning a range of over 300 km along the east coast of Florida. The study design allowed for a comparison of baseline residency and patterns of movement for unconstrained fish before, during, and after exposure to high-intensity pile-driving sounds.

2 Methods

2.1 Study Area

Port Canaveral is a multiuse harbor that supports cruise ships, fishing ports, and military testing and training activity. Specifically, the Port is composed of a main navigation channel running east–west as well as West, Middle, and Trident (east) Turning Basins (Fig. 58.1). The West Basin contains several cruise ship terminals, while Poseidon and Trident Wharves in the Middle and Trident Basins, respectively, are managed by the Naval Ordnance Test Unit as a US military facility.

The hard-bottom habitat and structure present from the expansive wharves and adjacent stone revetments within the Port create valuable habitats that have resulted

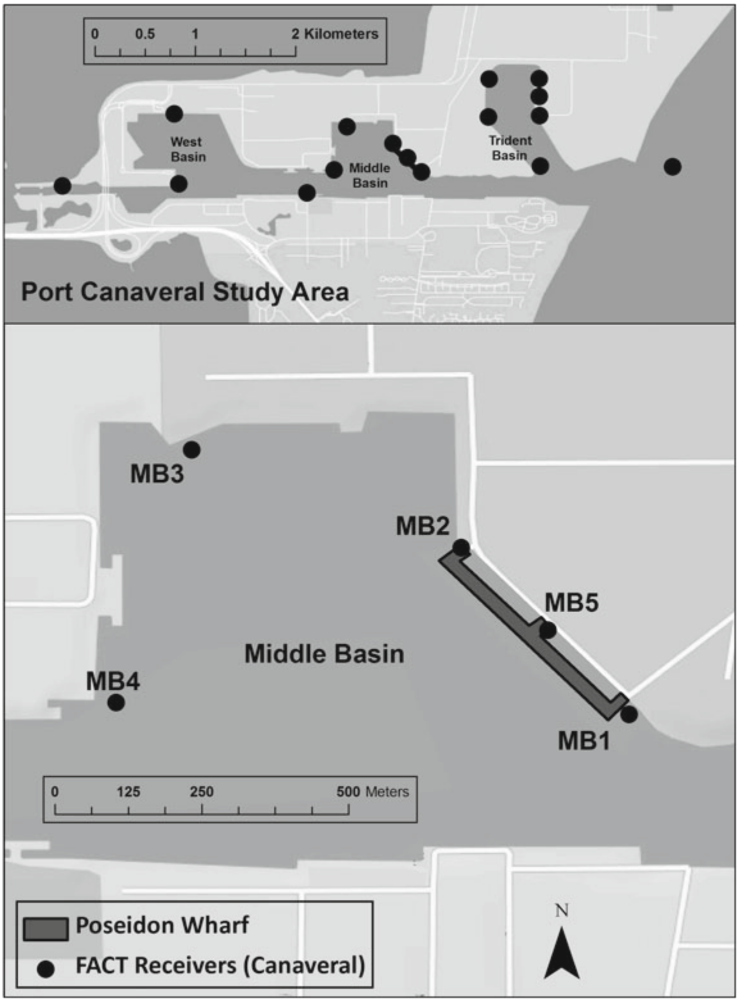

Fig. 58.1 *Top*: Port Canaveral study area with Vemco VR2W receivers (MB1–MB5; *circles*). *Bottom*: Pile driving occurred along Poseidon Wharf in the Middle Basin. *FACT* Florida Atlantic Coast Telemetry array

in robust resident populations of various tropical reef fish species (Reyier et al. 2010). Although these fish are exposed to low levels of anthropogenic noise regularly from activity at Port Canaveral, events that produce noise at the source levels typical of pile-driving construction are rare.

Pile-driving construction was part of a fender replacement project on Poseidon Wharf in the Middle Basin for 35 days in November and December 2011. The project involved removal of expired pressure-treated wooden piles and replacement with 104 polymetric fiberglass-reinforced concrete piles. The square polymetric piles were 16 in. on edge by 80 ft long and placed in two main sections along the center and northern outer faces of the wharf. Turbidity curtains were deployed around the pile extraction and placement operations to minimize water turbidity outside the work area. Bottom substrates in the dredged Port Canaveral harbor were considered fine sediment sand or muddy sand, and the approximate depth at the location of the pile driving was 10 m. No construction or other disturbance was occurring in the Trident Basin concurrent with the pile driving along the Poseidon Wharf, and the behavior of tagged fish in that location served as a separate control.

2.2 Acoustic Telemetry

Vemco VR2W autonomous telemetry receivers (Vemco Division, Amirix Systems, Inc.) were deployed in the West, Middle, and Trident Basins to supplement the existing Florida Atlantic Coast Telemetry (FACT) array (Fig. 58.1).

2.3 Collection and Tagging

For this study, a total of 15 sheepshead and 10 gray snapper were tagged in the Middle Basin and 12 sheepshead and 3 gray snapper were tagged in the Trident Basin. All fish were collected by either gill net or hook-line angling. Vemco V9-2 L acoustic transmitters (Vemco Division, Amirix Systems, Inc.) were 29 mm in length and 9 mm in diameter, had a weight of 2.9 g in water (4.7 g in air), and produced a 69-kHz unique coded signal with a nominal burst interval of 60–90 s at 146 dB re 1 μPa at 1 m. Target fish had a minimum weight of 300 g in air to ensure that the tag accounted for no more than 2% of body mass (Winter 1983). Fish were anesthetized in a seawater solution of 75 mg/L of tricaine methanosulfonate (MS-222, Western Chemical, Inc.) and allowed to fully recover in aerated seawater for 5–15 min before release.

Fish were collected 11 days before the start of construction to maximize collection of baseline data. The expected battery life of the Vemco V92L acoustic transmitters was ~11.5 mo.

2.4 Sound Recording

Recordings were made during 4 days of the event at a range of distances from 10 to 370 m from the pile driving. Source levels were measured 10 m from the pile being driven. Ambient recordings were taken when no piles were being driven. Equipment utilized in this effort included two calibrated Cetacean Research Technology (Seattle, WA) C55 hydrophones (mean sensitivity−165 dB re 1 V/μPa), two calibrated High Tech, Inc. (Long Beach, MS) HTI-96-Min hydrophones (mean sensitivity −185 dB re 1 V/μPa), and a DT9837 4-channel dynamic signal-acquisition module (Data Translation, Marlboro, MA). Conductivity, temperature, and depth profiles were gathered with a YSI 6920 datasonde (YSI Inc., Yellow Springs, OH).

Acoustic modeling in confined shallow-water environments such as the study site is challenging, particularly in the open spaces of the interior wharf where receivers MB1, MB2, and MB5 were located (Fig. 58.1). As a result, received levels for these areas within the interior portions of the wharf were based on empirical data recorded during the event. For open-water portions of the basins, transmission loss was modeled using the appropriate environmental data (temperature, salinity, and geoacoustic parameters) as defined in the shallow-water propagation-modeling tool (Navy Standard Parabolic Equation [NSPE] Range-dependent Acoustic Model [RAM]), and empirical measurements were utilized as a reference for the transmission loss calculated in the frequency domain. Received levels are presented as root-mean-square (rms) and peak pressure level. The rms values were calculated from the period of individual strikes accounting for 90% of the acoustical energy (California Department of Transportation 2009).

2.5 Residency

Raw detection data were filtered to minimize the probability of accepting false-positive detections (single coded detections within a 30-min window; Pincock 2008). Residency indices (RIs) were calculated for each tagged fish to represent the proportion of days detected on a receiver or group of receivers. RIs were calculated for individual receivers located at Poseidon (MB1, MB2, MB5) and Trident Wharves and for the full combination of receivers located at each wharf to examine broader scale residency at these structures. Baseline comparison of RIs for time periods was conducted utilizing the nonparametric Kruskal–Wallis test and IBM SPSS predictive analytics software. The Wilcoxon matched-pairs signed-rank test was used for post hoc comparisons between paired groups (before to during; during to after; before to after). Significant differences were considered at an α level of 0.017 after a Bonferroni correction for multiple comparisons. Before, during, and after construction timelines were 1–11 November 2011 (days 1–11), 12 November to 16 December 2011 (days 12–47), and 17 December 2011 to 20 January 2012 (days 48–82), respectively. One fish (ID 3023) was caught and harvested by anglers after 75 days of release and was removed from data analysis subsequent to these dates.

3 Results

3.1 Sound Recording and Received Levels

The measured broadband source level using a representative recording of a series of strikes collected 10 m from the pile-driving source was 182 dB re 1 μPa. This recording was utilized as the reference data file for propagation loss as computed by

NSPE RAM to obtain the received levels in subsequent analyses. Based on measured recordings along the outer and interior wharves, it is likely that fish present within close proximity to Poseidon Wharf were repeatedly exposed to levels in the range of 136–158 dB re 1 μPa rms for each strike over the duration of construction. During pile driving in the central portion of the outer wharf, measured received levels in the vicinity of the telemetry receiver MB5 located in the middle interior portion of the wharf was 136 dB re 1 μPa rms compared with 133 and 139 dB re 1 μPa rms for MB2 and MB1, respectively.

3.2 Residency

The number of fish of both species detected on three of the Middle Basin receivers (MB1, MB2, and MB5) along the interior of Poseidon Wharf from 1 November 2011 through 20 January 2012 is shown in Fig. 58.2. The highest number of fish was detected on receiver MB1, closest to the posttagging release site, followed by MB5, located in the center of Poseidon Wharf. The mean number of unique fish detected per day on the wharf decreased from 15.6 before pile driving to 11.7 and 11.3 during and after pile driving, respectively. No signs of mortality or injury to tagged fish were evident from the data of tagged individuals.

Median RI values for sheepshead in the Middle Basin increased on MB1 (south end of Poseidon Wharf) from 0.3 before construction to 0.5 after construction, while these values decreased on MB5 (closest to the pile driving) from 0.4 to 0.2.

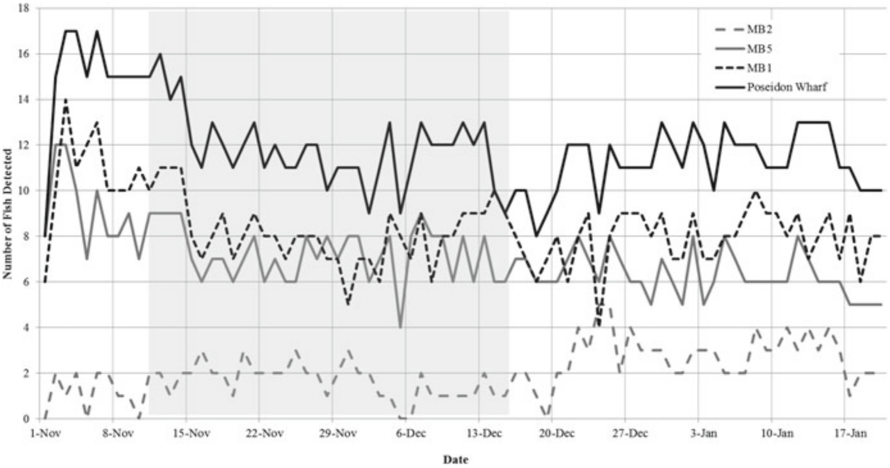

Fig. 58.2 Number of fish detected each day on three Middle Basin receivers (MB2, MB5, and MB1) located within Poseidon Wharf. The postsurgery release site was closest to MB1. Poseidon Wharf represents detection of a particular fish on any of the three receivers. *Gray shading* indicates days of active pile driving

Residency of sheepshead at MB2 farthest from the tagging release site was consistent with a median of 0 throughout the pile driving, and RI values for the Poseidon Wharf combined receivers stayed relatively constant, ranging from 0.82 before construction to 0.89 after construction. The median values for mangrove snapper decreased on MB1 from 0.45 to 0.01 and from 0.18 to 0.09 on MB5 between the before and after construction periods. The RI values for snapper on MB2 were consistently low, ranging from 0.02 to 0.04, and decreased from 0.58 to 0.18 after construction for the Poseidon Wharf combined receivers. There were significant differences in the RI among time periods for the mangrove snapper on MB1 ($H=7.99$, df=2, $P=0.018$) and for Poseidon Wharf combined ($H=9.63$, df=2, $P=0.008$), but no significant differences were observed for the sheepshead. Post hoc analysis showed that only the before-to-during construction decrease in the RI for the mangrove snapper on Poseidon Wharf combined was significant ($z=-2.50$, $n=10$, $P=0.013$).

At Trident Wharf, the median RI values for sheepshead ($n=12$) stayed fairly consistent across time periods, with a decrease in values at the receiver located at the middle of the wharf from 0.95 to 0.53 before to after construction. Statistical analysis performed for the sheepshead released in the Trident Basin showed no significant differences among time periods at any of the receivers or for the Trident Wharf combined. Analyses for the mangrove snapper captured in the Trident Basin were not performed due to the small sample size.

4 Discussion

This study was designed to examine the potential changes in residency of unrestrained reef fish in close proximity to impact pile driving. Timing of the fish collection was important to allow sufficient before construction baseline data for comparison with periods during and after construction. Given the success of monitoring tagged, unrestrained fish in the study area for a significant time period, it is unlikely that the pile-driving fender replacement resulted in mortality or significant injury to tagged individuals.

Receivers were deployed to maximize the detection of fish along the interior of Poseidon Wharf and in key areas at the north and south ends. Based on measured recordings along the interior of the wharf and 10 m from the source, it is likely that fish present at Poseidon Wharf were repeatedly exposed to received levels in the range of 136–158 dB re 1 μPa rms for each strike. It is likely that significant attenuation of the pile-driving sound along the inside of the wharf due to obstruction from pilings limited the intensity of sounds in this area and also limited any potential for injury or mortality to fish.

There were no major changes in residency observed for sheepshead along Poseidon Wharf during the pile-driving event; however, there was a significant decrease in snapper residency on Poseidon Wharf receivers from the before to during construction time periods. Mangrove snapper are opportunistic predators and likely move between habitats and basins more readily than sheepshead. Poseidon Wharf is also contiguous, with a well-developed subtidal rock revetment, and fish do not have to traverse open water to move away from the wharf or even into the adjacent Trident Basin. As a result, the decrease in snapper residency at Poseidon Wharf during the construction is most likely a result of normal movements for gray snapper in this location.

There are several potential responses of fish to anthropogenic acoustic disturbance, ranging from immediate reactions such as a startle or alarm response to longer term changes in natural behavior. Behavioral response can vary based on a number of factors, including location at the onset of disturbance, dependency on the study area for key life history traits, and habituation to the source over the short term. Mangrove snapper may be more susceptible to displacement because these fish typically school on the fringes of the outer wharf and were therefore potentially exposed to higher levels of sound.

As described above, examination of the potential behavioral impacts to fish species must account for the baseline behavior of fish and characteristics of the study area that may affect individual behavioral response. Additionally, examination of the impacts of high-intensity sound to fish other than reef fish should include potential alteration of migration patterns, site fidelity, distribution, and associated consequences to survivorship.

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Chapter 59
Hidden Markov Models Capture Behavioral Responses to Suction-Cup Tag Deployment: A Functional State Approach to Behavioral Context

Saana Isojunno and Patrick J.O. Miller

Abstract The biological consequences of behavioral responses to anthropogenic noise depend on context. We explore the links between individual motivation, condition, and external constraints in a concept model and illustrate the use of motivational-behavioral states as a means to quantify the biologically relevant effects of tagging. Behavioral states were estimated from multiple streams of data in a hidden Markov model and used to test the change in foraging effort and the change in energetic success or cost given the effort. The presence of a tag boat elicited a short-term reduction in time spent in foraging states but not for proxies for success or cost within foraging states.

Keywords Behavioral state • Proxies • Animal-attached tags • Tagging effects • Bayesian

1 Introduction

There is an increased understanding that a simple received sound pressure level dose–response approach is not sufficient to precisely predict the probability of a behavioral response for wild marine animals (e.g., Beale 2007; Ellison et al. 2011). First, dose metrics need to move toward sensation levels that account not only for sound propagation but also for the signal-to-noise ratio levels in the environment, the hearing threshold of the receiver at specific frequency spectra, and the exposure in terms of the temporal characteristics of the signal (Madsen 2005; Nowacek et al. 2007; Southall et al. 2008; Ellison et al. 2011). Second, signal perception and tolerance level may also vary with behavioral context, internal state, and experience (Beale 2007; Southall et al. 2008; Bejder et al. 2009; Ellison et al. 2011),

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particularly at lower received levels (Ellison et al. 2011). An ability to modify the perception of a threat through experience is likely to be an adaptive trait in many species and may lead to habituation or sensitization over time (Bejder et al. 2009). Behavioral and environmental context, in turn, can determine whether a noise is perceived as a cost or a nuisance to current activity and what other behavioral options are available, such as modifying the vocal output (Lombard effect; Hotchkin and Parks 2013) or leaving the habitat (Gill et al. 2001; Lusseau and Bejder 2007). Finally, an individual's age and physiological and energetic state might influence the cost, benefit, or even ability to respond (e.g., Beale and Monaghan 2004). Thus, the probability or intensity of a behavioral response does not necessarily have a simple positive relationship with the vulnerability of an individual (Gill et al. 2001; Beale and Monaghan 2004; Beale 2007).

A more comprehensive evaluation of the environmental and individual context could be incorporated within the dose–response framework to improve the accuracy and precision of the estimated function in real-world situations (Ellison et al. 2011). Many of these contextual variables can be controlled or measured during controlled exposure experiments, but careful inference and complementary observational data are needed to extrapolate short-term responses to long-term and real populations (Lusseau and Bejder 2007; Tyack 2009). Indeed, the probability of any response doesn't directly address the fitness and population consequences that ultimately motivate conservation biology. From the "ecology of fear" perspective, nonlethal but chronic effects of predators such as increased vigilance can impact populations even more than lethal effects (Brown et al. 1999). Anthropogenic effects can be expected to be partly antipredatory because prey have evolved to respond to, and even overestimate, generalized threatening stimuli (risk-disturbance hypothesis: Frid and Dill 2002; Curé et al. 2013). With mounting evidence of such behavioral impacts, conservation behavior seeks to develop predictive tools to identify early warning indicators of a numeric (population) response and monitor the effectiveness of management programs (Berger-Tal et al. 2011). A dose-severity framework is emerging but to date relies on expert judgment on what behavioral effects translate into severe impacts (Southall et al. 2008; Miller et al. 2012).

With advances in biotelemetry (Cooke et al. 2004; Johnson et al. 2009), a promising approach is to use tag sensor data to derive metrics that can proxy benefits and costs of behavior, such as energy (e.g., proxies of active expenditure from tri-axis accelerometers; Wilson et al. 2006), information (e.g., biosonar target range estimates; Madsen et al. 2005), conspecific associations (e.g., vocal response indicates initiation of social behavior; Curé et al. 2013), or body condition (e.g., drift rates related to buoyancy; Biuw et al. 2003). These currency proxies make an implicit assumption of the proximate or ultimate motivation of behaviors and are therefore more directly linked to the biological consequences of behavior. Typically, proxies are measured over a study window or time windows that match the duration and spatial scale of the relevant behavior (such as prey encounter rates during foraging phases; Watwood et al. 2006). A more realistic approach is to allow these windows or behavioral states to vary over time (state switching). States may be classified directly from the data ("behavioral state"), such as an area-restricted search, or refer to an underlying motivation that drives the observed behavior ("motivational state"; Bindra 1978), such as hunger level. Internal and external drivers of behavior may be combined by considering a behavioral time series arising from discrete functional units ("functional states") that are associated with the fulfillment of a particular proximate or ultimate goal or set of goals based on a priori hypotheses (Nathan et al. 2008). With advances in statistical computing, there is an increasing scope to estimate these states within more realistic hidden process models that distinguish the observation and underlying ("hidden") process explicitly (Patterson et al. 2008; Schick et al. 2008).

Here we extend the movement ecology paradigm by Nathan et al. (2008) to include behaviors other than movement and propose that motivating currencies should be used in conjunction with state modeling to measure the achievement (success rate) of the goals of a functional state (Fig. 59.1). Thus, if motivating currencies can be estimated given a state, fitness consequences can be evaluated with or without

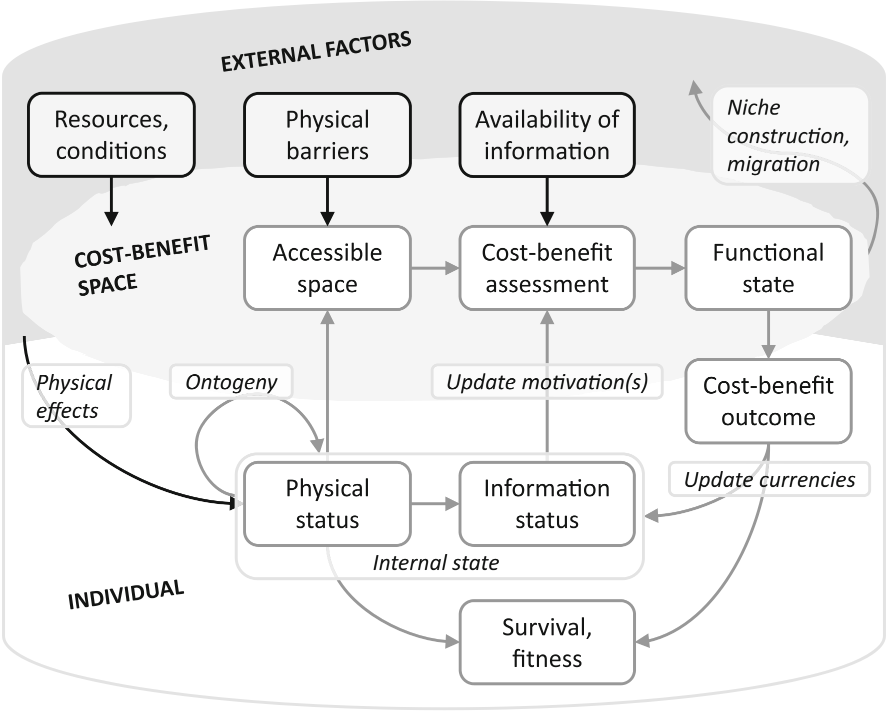

Fig. 59.1 A framework for context-dependent behavior, inspired by Nathan et al. (2008). The "functional state approach" consists of the focal individual, its biotic and abiotic environment (external factors), and their interface (cost-benefit space). Cost-benefit space is the outcome of behavioral options available to an individual, such as a trade-off between quantity and quality of offspring. Behavioral options are associated with a set of proximate goals or ultimate motivations (e.g., food, shelter). These options are limited physically and physiologically (accessible space) through individual history (ontogeny, sexual maturity), current physical status (reproductive state, body condition, and homeostasis), and physical barriers. Cost-benefit assessment is the internal mechanism for selecting a behavioral option. Information status encompasses cues, information, and memory from both sensory and nonsensory inputs in the somatic nervous system. Functional state is the realized behavioral option and gives rise to a collection of behavioral traits that may influence the focal environment (niche construction). Currencies measure the cost-benefit outcome of the functional state and feed back to the internal state of the individual, with carry-over effects on subsequent behavioral options, functional states, and fitness

evidence of a specific behavioral response. This “functional state approach” helps to frame the cross-disciplinary links between the motivating currency, proximate constraints, and ultimate consequences of behavior and to encourage the view that behavioral context is a signal rather than a noise variable that could potentially fill in knowledge and data gaps of individual-based approaches to population consequence. We do not suggest that all components in the concept model should be explicit; rather, their omission can be stated and assumptions justified within a common conceptual framework.

We briefly illustrate a method that estimates hidden functional states, including an active nonforaging state, from multiple fine-scale streams of DTAG data for foraging *Physeter macrocephalus* (sperm whales). We used these states to control for variability in proxies for energetic benefit and cost and formulated three hypotheses for the behavioral effects of tag deployment procedures: (1) a change in foraging effort; (2) a change in energetic cost, given the effort; and (3) a change in energetic benefit, given the effort. The three hypotheses were tested to establish a baseline period for use in controlled exposure experiments.

2 Methods

DTAG (Johnson et al. 2009) data from 12 individual sperm whales were used to parameterize the hidden state model, including animals tagged as part of Danish collaborative research with Mark Johnson in 2005 (Teloni et al. 2008) and the 3S project near the Lofoten Islands in 2008–2010 (Miller et al. 2012). Data were excluded for three whales that were incidentally exposed to unidentified sonar immediately after being tagged and during all experimental exposures and postexposure periods. The remaining data included 9 DTAG deployments from the time of the first tagging to the first exposure/silent control or end of the full tag record. We included the tagging and posttagging periods of two deployments that were reapproached for a secondary tag attachment. For all analyses, DTAG depth data were downsampled to 1 sample/min. The mean pitch and presence of echolocation (aurally verified regular or buzz clicking) were calculated over consecutive 1-min blocks.

We specified six functional states for sperm whales in a high-latitude foraging ground: (1) surfacing: oxygen replenishment and physiological recovery at the surface; (2) descending transit: transiting to a deeper prey layer; (3) layer-restricted search (LRS): searching at a prey layer; (4) ascending transit: transiting to a shallower depth or the surface; (5) resting: sleep and physiological recovery underwater; and (6) other nonforaging, undefined functions (e.g., antipredatory or social behavior). The states were built into a discrete-time hidden-state model that described how observed data arose from the unobserved or “hidden” states in terms of likelihoods. Thus, the states were not a preclassified model input but were estimated from data given state-specific likelihoods.

The hidden-state model consisted of a 6×6 transition matrix for the Markov conditional probability of state transition and the state-specific likelihoods for depth, presence of clicking, and absolute value of pitch angle. Depth was modeled as a Gaussian random walk with switching between directional (descend and ascend states) and nondirectional transit. Each state estimated a Bernoulli probability of clicking. Pitch was modeled in a log-linear beta regression with state-specific intercepts and a single coefficient for a vertical step for all mobile states (i.e., not surfacing or resting). Models were parameterized using a Gibbs sampler software jags within R package R2Jags and coda (3 chains with 16,000 iterations each). Descent and ascent rates were specified using informative prior values from the literature (Watwood et al. 2006). The probability of clicking for surfacing, resting, and other functions was assigned a low mean prior value. Convergence was monitored both visually and by formal diagnostics (Brooks and Gelman 1998).

Tagging effects were tested on three response variables in a generalized linear regression: (1) state (multinomial, proxy for foraging effort), (2) presence of a buzz (binomial, proxy for prey encounter rate; Miller et al. 2004), and (3) overall dynamic body acceleration (ODBA; Gaussian, proxy for movement cost; Wilson et al. 2006). Candidate baseline covariates included previous state (prevState) in models for state (i.e., presence of a state, given the previous state) and state in models for buzz and ODBA (foraging success/cost, given the effort). All models included the tag identifier as a factor (whaleName). Candidate covariates for tagging effects aimed to capture different hypotheses for an abrupt and/or decaying dose that may have elicited a response: (1) minutes since tag-on time (minFromTot), (2) tagging boat presence/absence on water (tagging), (3) number of minutes since tagging (minFromTagging), and (4) minFromTagging squared (minFromTagging^2). The models were fit using the functions multinom and glm in R libraries nnet and stats, respectively. To avoid overfitting and collinear effects, a forward stepwise selection was carried out on five subsets of independent covariates.

3 Results and Discussion

When the tag boat remained in the water ($n = 7.7$ h), the whales spent no time resting but spent nearly 6× more time in an active, nonforaging state (21.4%, SD = 41.0) and less than half the time at the surface (9.7%, SD = 29.7) compared with the baseline periods when the boat was recovered ($n = 78.9$ h; 3.6%, SD = 18.6 and 21.8%, SD = 41.3, respectively; Fig. 59.2). Based on the Akaike information criterion (AIC), prevState, whaleName, and tagging were retained in models for state (8,618.5, 163.1, and 18.4 AIC score decrease, respectively), whereas only state and whaleName were retained in models for buzz and ODBA. Thus, tag boat presence was an important predictor of the states related to the foraging effort but did not explain the success or cost, given the effort. No longer term changes were detected (minFromTot, minFromTagging, and minFromTagging^2 were not retained in model selection).

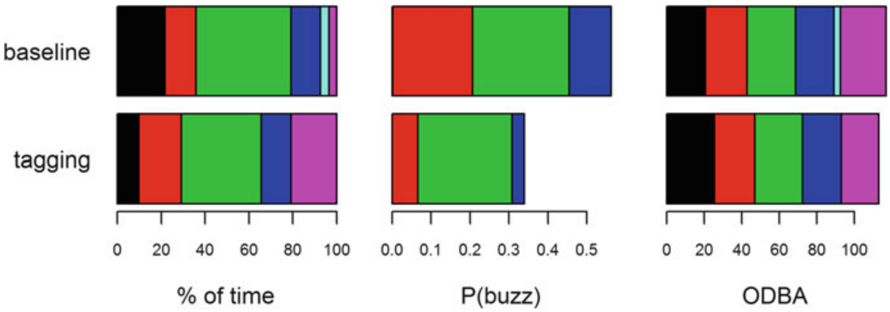

Fig. 59.2 Proxies of foraging effort (percent of time spent in each state) and success (probability of buzzing [P(buzz)]) and cost (mean overall dynamic body acceleration [ODBA]) of each state during the tagging condition (tag boat on water, 7.7 h) and baseline (78.9 h). Effort was composed of six states: surfacing (*black*), descending transit (*red*), layer-restricted search (*green*), ascending transit (*dark blue*), resting (*light blue*), and other nonforaging (*pink*)

These results indicate a direct annoyance or vigilance reaction to the presence of the tag boat, with a reduced time in states with a foraging effort but no longer term effects on the scale of each tag record (~15–20 h in duration).

The developed method appears to be an effective approach in estimating the behavioral responses that are more directly linked to individual fitness; it formalizes prior expectation of behavior, combines multiple sources of data to estimate biologically interpretable states and parameters (such as descent rate), and accounts for the motivational-behavioral context of currency proxies. Although the hidden-state model excluded many of the processes that influence functional states (a decision mechanism, currency feedback, individual effects, and exposure; Fig. 59.1), it succeeded in estimating variable time budgets between tagging and baseline periods and across individuals. This highlights that hypothesis-based states can reduce the complexity of behavioral context in a biologically meaningful quantification of response.

There are three major applications that make hidden-process and state-switching models relevant to future conservation research. First, response intensity can be specific to context; decision-making mechanisms such as resource selection can be formulated to vary with or be specific to a state (e.g., Getz and Saltz 2008). Second, changes in internal state can feed back to behavior; the probability of switching to or staying in a state can be modeled as a function of subject-specific explanatory variables such as body mass (e.g., Schliehe-Diecks et al. 2012). Third, incorporating state-switching and individual effects allows for more behavioral complexity that may be crucial for scaling up from individual-level processes to population-level phenomena, such as social group dynamics (Marshall et al. 2012) and demographic rates (McNamara and Houston 1996; Schick et al. 2008; Morales et al. 2010). For example, nested motivational states emerged naturally at the three nodes of the population consequences of acoustic disturbance (PCAD) framework (National Research Council 2005): behavioral states (e.g., surfacing: harvest oxygen), life history states (e.g., migration: find mates), and population states (e.g., juvenile: survive and maximize body condition). We envision progress by quantifying context dependencies across these scales within a more common conceptual framework, developing process models that can borrow strength across individuals and species and increasing integration of experimental, observational, and multiscale data.

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Chapter 60
A Change in the Use of Regulatory Criteria for Assessing Potential Impacts of Sound on Fishes

Fred Jacobs, Justin Krebs, and Arthur N. Popper

Abstract The National Marine Fisheries Service (NMFS) currently uses interim criteria developed on the US West Coast to assess the potential onset of peak and cumulative effects of noise on fishes. Analyses performed for this project provided adequate support for the NMFS to use the peak criterion (i.e., area ensonified by 206 dB re 1 μPa peak sound pressure level [SPL_{peak}]) for estimating the incidental take of Hudson River sturgeon. Application of the peak criterion (rather than the cumulative criterion) could have implications for future construction projects because estimates of take using SPL_{peak} will generally be considerably lower than estimates of take based on the cumulative sound exposure level.

Keywords National Marine Fisheries Service • Sturgeon • Hydroacoustics • Regulatory criteria • Pile driving

1 Background

In the United States, the National Marine Fisheries Service (NMFS) currently uses interim criteria developed on the US West Coast to assess the potential onset of physiological effects on fishes due to noise from pile-driving effects (reviewed in Stadler and Woodbury 2009). These interim criteria were developed by the Fisheries Hydroacoustic Working Group (FHWG), which consisted of biologists from the NMFS, the US Fish and Wildlife Service (USFWS), the Federal Highway Administration (FHWA), and the Departments of Transportation from California,

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Washington, and Oregon. Although the criteria were developed for west coast species, the NMFS has been applying these criteria in determining allowable take for construction projects at various locations around the country where noise impacts may occur.

The interim criteria are (1) 206 dB re 1 μPa peak sound pressure level (SPL_{peak}), (2) 187 dB re 1 $μPa^2$·s cumulative sound exposure level (SEL_{cum}) for fish weighing >2 g, and (3) 183 dB re 1 $μPa^2$·s SEL_{cum} for fish weighing <2 g.

SPL_{peak} is a measure of instantaneous peak noise exposure, whereas SEL_{cum} is a metric that accumulates the total exposure received by an animal over the duration of exposure. SEL_{cum} is the logarithmic addition of the energy in single exposures or, in this case, pile-driving strikes, referred to as SEL_{ss}. SEL_{cum} thereby reflects prolonged exposure to pile driving (or any sound), with the assumption that fish remain in ensonifed areas during pile driving for a period long enough to accumulate the required exposure.

These interim criteria were accepted by the parties through a Memorandum of Agreement (MOA) in 2008, with the recognition that as new information became available, the interim criteria could require modifications.

2 Recent Studies

Since the 2008 MOA, a number of studies on the effects of pile-driving sounds have been performed (e.g., Bolle et al. 2012; Halvorsen et al. 2011, 2012a, b; Casper et al. 2012, 2013a, b). These studies demonstrated that the West Coast interim criteria are overly conservative and that fish species evaluated in laboratory tests did not suffer injury or mortality until the fish were exposed to much higher noise levels. These studies exposed six species, with broad differences in body plan, to very high intensity sounds that were based on actual pile-driving signals. Results showed that the onset of physiological effects only occurred when the SEL_{cum} exceeded 207 dB re 1 $μPa^2$·s and that mortal injuries did not occur until the SEL_{cum} was 6–10 dB higher (see Popper et al. 2013; Chapter 14 by Casper et al.). Moreover, it was shown that a species without a swim bladder showed no physiological effects at the highest sound levels that could be generated (Halvorsen et al. 2012b) and that fish, when maintained in the laboratory, recovered fully within 10 days (Casper et al. 2012, 2013b). Of considerable significance was the finding that damage to the sensory cells of the inner ear, a potential harbinger of hearing loss (Smith et al. 2006), did not show up until the SEL_{cum} was well above the levels needed to produce other physiological effects associated with the swim bladder or structures near the swim bladder (Casper et al. 2013a).

Taken together, these studies and those by Bolle et al. (2012; see Chapter 10 by Bolle et al.) showed that the onset of physiological effects in widely diverse species show up at SEL_{cum} levels that are 20 dB or higher than the current interim criteria. Moreover, the results demonstrate that the actual effect on the physiology (referred to as barotrauma) is a result of a combination of the SEL_{ss} of individual strikes and the number of actual strikes, although there is no one-to-one relationship and so the proposed "equal energy hypothesis" for effects (Stadler and Woodbury 2009) is not correct (Halvorsen et al. 2011, 2012a).

3 New NY Bridge

As discussed in Chapter 106 by Popper et al., a new bridge (New NY Bridge) will be constructed to replace the aging Tappan Zee Bridge over the Hudson River. As part of the permitting process for this replacement bridge, extensive analyses of potential pile-driving impacts to two long-lived endangered species, shortnose sturgeon (*Acipenser brevirostrum*) and Atlantic sturgeon (*Acipenser oxyrinchus*), were performed. Both species must transit through the vicinity of the bridge construction area on their migrations to and from upriver spawning grounds and to reach overwintering areas. The evaluation of the initial bridge concept assessed the impact of driving more than 1,000 steel pipe piles ranging in size from 1.22 m (4 ft) to 3.05 m (10 ft) in diameter. The final bridge design consists of 916 piles plus 15 test piles and eliminates the use of the 2.44-m- (8-ft-) and the 3.05-m- (10-ft-) diameter piles, which were the sources of the greatest noise impacts. Extensive consultation with the NMFS and the New York State Department of Environmental Conservation (NYSDEC) occurred throughout the permitting process. The technical analyses that led to the estimates of sturgeon take were performed by the project sponsors and are described in several documents including the Final Environmental Impact Statement (FEIS; 2012) for the replacement bridge, the Revised Biological Assessment (FEIS 2012, Appendix F-10), the two NMFS Biological Opinions (BOs; NMFS 2012a, 2013), and Chapters 67 by Krebs et al. and 68 by Krebs et al. The analyses performed considered the effects on sturgeon using both SPL_{peak} and SEL_{cum} criteria.

Previous BOs issued by NMFS have typically relied on dual criteria (SPL_{peak} and SEL_{cum}) for assessing pile-driving impacts but have more commonly used the SEL_{cum} for determining incidental take of federally listed fish species in coastal systems. However, in the case of the New NY Bridge (to replace the existing Tappan Zee Bridge), discussions with the NMFS and the technical analyses conducted by the project sponsors provided adequate support for the NMFS to apply the peak criterion (i.e., the area ensonified by 206 dB re 1 μPa SPL_{peak} or greater) for estimating incidental take of Hudson River sturgeon (NMFS 2012a, 2013).

The rationale for the NMFS decision was that the SEL_{cum} is a measure of prolonged exposure and for it to be relevant, the fish must stay in the ensonified area throughout the number of pile strikes factored into the noise estimate. The NMFS indicated that they did not expect sturgeon to remain close enough to the piles being driven for a long enough period to experience prolonged exposure because sturgeon would be expected to “react behaviorally and move away from the source of the noise” (NMFS 2013, p. 82). In short, sturgeon will avoid pile driving and will therefore not remain in proximity during active pile driving long enough to accumulate sufficient sound energy to reach the cumulative criterion.

The recognition that the peak criterion was the appropriate metric for determining sturgeon take for the proposed New NY Bridge construction was strongly supported by a study of acoustically tagged Atlantic sturgeon conducted in the project vicinity during a preconstruction Pile Installation Demonstration Project (PIDP) and described in Chapter 67 by Krebs et al. That study indicated that time spent by sturgeon in a relatively large tag-detection area was significantly less during pile driving than during periods immediately before pile driving as demonstrated by statistical analysis. It appears that tagged Atlantic sturgeon avoided the area in the vicinity of pile-driving activities when impact hammers were used and sturgeon did not remain in the vicinity of pile driving for long enough periods to accumulate enough energy to cause injury based on the $\mathrm{SEL_{cum}}$ criterion. During the PIDP, only 1 out of 155 fish that were detected had more than a 1% probability of reaching the 187 dB re 1 $\mu\mathrm{Pa^2 \cdot s}$ criterion for the onset of physiological effects.

In addition to developing specific numbers of affected shortnose and Atlantic sturgeon for incidental take based on the $\mathrm{SPL_{peak}}$ criterion, the NMFS is also using the peak criterion in other ways as a proxy for determining incidental take for the duration of the project. For example, the NMFS will consider whether incidental take is exceeded if the geographic extent of the area where noise is >206 dB re 1 μPa is greater than the area used to calculate the number of fish affected in the BO (NMFS 2013). Therefore, if the monitoring data indicate that the distance from the pile to the $\mathrm{SPL_{peak}}$ exceeds the distance used to calculate take (i.e., 6.1 m for the 1.22-m pile), then the NMFS may consider that incidental take has been exceeded.

The NYSDEC, which also weighed the use of both the peak and the cumulative criteria for assessing pile-driving impacts, ultimately agreed with the NMFS and also relied on analyses using the peak criterion to develop allowable sturgeon take for the State’s incidental take permit. The permit was granted to the project sponsors in March 2013 and had the same allowable incidental take for injured or stunned shortnose and Atlantic sturgeon (41 for each species), as did the NMFS in their permit.

However, neither the NMFS nor the NYSDEC totally abandoned the $\mathrm{SEL_{cum}}$ for setting performance criteria for sturgeon protection. Both agencies are requiring that during pile-driving activities, the project sponsors maintain a 1,524-m (5,000-ft) corridor across the Hudson River where the accumulated sound level never exceeds a $\mathrm{SEL_{cum}}$ of 187 dB re 1 $\mu\mathrm{Pa^2 \cdot s}$ during impact hammering. The corridor may be broken into contributing segments, but none can be smaller than 457 m (1,500 ft). This permit condition attempts to ensure that there will always be sufficient nonensonified areas for fish to move freely through the construction area during spawning migrations or other transit up and down the river.

4 Implications for Bridge Construction Projects

Application of the peak criterion (rather than the cumulative criterion) by the NMFS and NYSDEC could have implications for future construction projects because incidental take estimates based on the peak criterion will be lower than comparable incidental take estimates based on the $\mathrm{SEL}_{\mathrm{cum}}$. For example, Table 60.1 indicates the distances from the pile to the $\mathrm{SPL}_{\mathrm{peak}}$ and $\mathrm{SEL}_{\mathrm{cum}}$, corresponding to the onset of physiological effects on sturgeon due to pile driving. It is clear that for the 1.22-m- (4-ft-) diameter piles, the radius of the $\mathrm{SPL}_{\mathrm{peak}}$ is 3–6 times shorter than the radius of the ensonified zone for the $\mathrm{SEL}_{\mathrm{cum}}$. For the larger 1.83-m- (6-ft-) diameter pile, the difference is about five times greater.

An analysis was also performed comparing the number of shortnose sturgeon that would exceed the $\mathrm{SPL}_{\mathrm{peak}}$ and $\mathrm{SEl}_{\mathrm{cum}}$ for the most recent construction scenario developed for the New NY Bridge. The analysis indicated that the number of shortnose sturgeon that may experience the onset of physiological effects due to pile driving was 41 using the $\mathrm{SPL}_{\mathrm{peak}}$ criterion and 111 shortnose sturgeon using the $\mathrm{SEL}_{\mathrm{cum}}$ criterion. After a comprehensive review, the NMFS (2013) used these data and considered incidental take exceeded if more than 41 shortnose sturgeon were observed injured or stunned. The analyses that formed the basis of these determinations relied on field data of piles being driven with noise attenuation systems in place.

Use of the $\mathrm{SPL}_{\mathrm{peak}}$ criterion would, therefore, appear to be the applicable metric for evaluating the effects of noise on other highly mobile fish species. Indeed, the NMFS (2012b) cited the work of Krebs et al. (2012) and went on to say that "due to the mobile foraging habits of sea turtles, smalltooth sawfish, and sturgeon, these species are likely to avoid annoying levels of noise and avoid any harmful effects from long-term exposure (hours)" (NMFS 2012b, p. 65). The NMFS then indicated that they were discounting any effects of cumulative exposure in their effects analysis for these marine species.

The work reported here represents an example of how the latest research findings on the effects of sound on fishes and the dialogue with regulatory agencies can be used to advance the use of appropriate guidance criteria. It is expected that in the future, BO analyses will focus on the $\mathrm{SPL}_{\mathrm{peak}}$ metric for assessing noise impacts to mobile coastal and migratory species.

Table 60.1 Distance from piles to $\mathrm{SPL}_{\mathrm{peak}}$ and $\mathrm{SEL}_{\mathrm{cum}}$ that corresponds to onset of physiological effects on shortnose sturgeon from pile driving with impact hammers and noise attenuation systems

	206 dB re 1 μPa $\mathrm{SPL}_{\mathrm{peak}}$	187 dB re 1 $\mu\mathrm{Pa}^2{\cdot}\mathrm{s}$ $\mathrm{SEL}_{\mathrm{cum}}$
Pile diameter	Distance from pile	Distance from pile
1.22 m (4 ft)	6.10 m (20 ft)	19.2–40.23 m (63–132 ft)
1.83 m (6 ft)	30.48 m (100 ft)	153.92 m (505 ft)

SPL_{peak} peak sound pressure level, *SEL_{cum}* sound exposure level

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Chapter 61
In-Air and Underwater Hearing in the Great Cormorant (*Phalacrocorax carbo sinensis*)

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Abstract Hearing thresholds of a great cormorant (*Phalacrocorax carbo*) were measured in air and under water using psychophysics. The lowest thresholds were at 2 kHz (45 dB re 20 µPa root-mean-square [rms] in air and 79 dB re 1 µPa rms in water). Auditory brainstem response measurements on one anesthetized bird in air indicated an audiogram with a shape that resembled the one achieved by psychophysics. This study suggests that cormorants have rather poor in-air hearing abilities compared with other similar-size birds. The hearing capabilities in water are better than what would have been expected for a purely in-air adapted ear.

Keywords *Phalacrocorax carbo sinensis* • Underwater hearing • Psychophysical measurements • Auditory brainstem response • Playback

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1 Introduction

Birds constitute a diverse class of more than 10,000 species. Many birds are well known for their vocal abilities, and sounds have an important communicative function in many or all species. The hearing sensitivity and the frequency range of hearing in most birds is less than what is found in most mammals (Dooling et al. 2000). Despite this, sound is used not only for communication but also for orientation and prey detection (Sibley 2001) and in very few species as a primitive form of echolocation (Griffin 1958).

More than 800 species of birds are aquatic in the sense that they forage underwater. Food sources can be seaweed, mollusks, polychaetes, shrimps, crabs, squid, and other invertebrates as well as fish of very different sizes and behavioral traits. Some birds go for schooling fish such as smaller clupeids or sand eels, whereas others chase single fish such as gobies and flatfish that are sometimes well hidden on the seafloor or in kelp beds (Johnsgard 1993; Einarsson et al. 2004).

Even though there have been many studies on the hearing ability of birds in air, there is currently no psychophysical or behavioral data on how birds hear or react to sound underwater (Dooling 2012). Aquatic birds show many anatomical adaptations to their in-water life form and, in some species, their senses (such as vision) are adapted to the underwater environment, for instance, regarding accommodation (Levy and Sivak 1980; Strod et al. 2004). Many marine mammals and some aquatic reptiles have adaptations for hearing underwater (Kastak and Schusterman 1998; Thewissen and Nummela 2008). Thus, it would not be surprising if some marine birds were adapted to hear underwater. This would make them able to communicate, to find prey, and to orient more efficiently while being submerged.

2 Methods

In the present pilot project, we measured the hearing ability of the great cormorant, *Phalacrocorax carbo sinensis*, using psychophysics, auditory brainstem responses (ABRs), and behavioral observations during playback of sound in air and under water. The study subject of the psychophysical measurement was a 2-year-old male cormorant (named "Loke"). Loke was wild caught and brought to the marine laboratory at the University of Southern Denmark in Kerteminde in September 2010 when he was ~4 month old. In June 2012, an additional cormorant (female fledgling named "Embla") was caught and added to the enclosure.

2.1 Psychophysical Measurements

The birds were fed 200–400 g of fish/day and trained using standard operant conditioning techniques with positive reinforcement. Figure 61.1 shows an outline of the psychophysical experiments performed in air and in water. The experimental

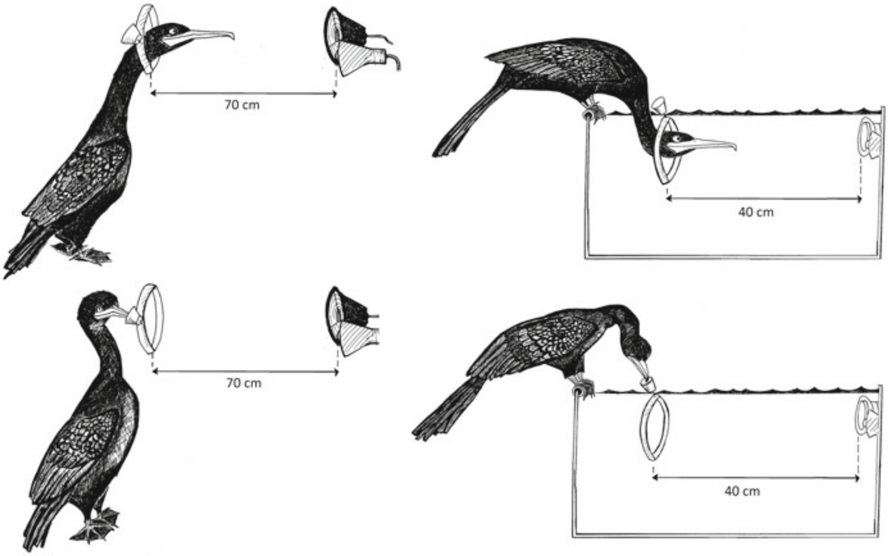

Fig. 61.1 Experimental setup for psychophysical measurements in air (*left*) and in water (*right*). Bird listens for a sound stimulus (*top*) and answers it correctly (*bottom*)

equipment was controlled by a custom-made Labview program that accepted input from a custom-built console connected to the data-acquisition system. A trial was initiated by the bird stationing with its head in a hoop. When the bird was stationed, the experimenter pushed a button on the console and the program turned on a lamp in front of the animal for 2 s. The lit lamp indicated the interval, during which the bird should listen for the tone. During GO trials, a 500-ms tone of a specified frequency and intensity was played out from the loudspeaker. Whether a trial was a GO or a NOGO trial was indicated by a previously made pseudorandom sequence following the rules of Gellermann (1933). For a NOGO trial, the correct response by the bird was to remain in the hoop, whereas for a GO trial, the bird should leave the hoop and touch the response button with its beak (Fig. 61.1).

The performance of the bird was logged by the experimenter using the console. If the previous GO response was correct, the sound level was decreased by 5 dB for the next GO trial, whereas if the previous response was incorrect, the signal level was increased by 10 dB. The hearing threshold was determined from the average of the sound levels at each incorrect GO and the preceding correct GO response was calculated. A total of ten sessions were made at each frequency in air and in water, with each session consisting of 30–35 trials. Fourteen of the in-water sessions were double-blind, where the experimenter wore headphones playing loud music while performing the experiments. The thresholds derived from double-blind and non-double-blind trials did not differ in any systematic way. The ambient-noise levels were recorded, and the spectral noise was estimated with MATLAB by averaging the power spectra overlapping 50% and calculated throughout the 1-min recording. Thresholds were compared with Student's *t*-test.

2.2 Psychophysical Measurements in Air and Under Water

In air, the bird was stationed in a 10-cm-diameter rubber hoop facing a loudspeaker and a lamp. The sessions were made at the frequencies of 1, 2, 4.5, and 6 kHz. The sound field at the position of the bird's head in the hoop varied from 3 to 13 dB, with the largest variations at the highest test frequency. The initial received level was 92, 70, 80, and 85 dB re 20 µPa root-mean-square (rms) for the 1-, 2-, 4.5-, and 6-kHz trials, respectively.

For the in-water trials, the bird was stationed on the short side of an 80- × 60- × 50-cm plastic pool (Fig. 61.1). The 10-cm rubber hoop was situated right below the water surface in front of the bird, and the underwater lamp and loudspeaker was situated at the other end of the pool. The bird lowered its head below the water surface through the hoop during the trial. The initial received level was 132, 148, 151, and 159 dB re 1 µPa rms for the 1.5-, 2-, 4.5-, and 6-kHz trials, respectively. Ambient-noise levels were measured right after each trial for 1 min. The sound field at the site of the bird's head in the hoop varied by 3–4 dB. The particle motion of the sound field was estimated by simultaneously recording the stimuli using two hydrophones kept in a plastic holder and spaced 3 cm apart. The particle motion was within three to four times the calculated free-field particle motion in any Cartesian direction and for any of the tested frequencies.

2.3 ABR in Air

An additional wild cormorant chicken ~1 month old was brought to the University of Southern Denmark. It was anesthetized, and the ABR was measured in a 150- × 100- × 80-cm soundproof box using three electrodes inserted subdermally on the skull with the active electrode above the ear. The stimulus was presented using a Sony woofer, and the response was measured using a digital signal processor. The measured response was based on the click response ABR and the response to a masker tone presented at different intensities and frequencies (250, 500, 1,000, 2,000, 4,000, and 6,000 Hz). The ABR was measured for 1 min for each frequency, and the stimulus was played back 400 times.

2.4 Behavioral Responses to Playback Trials in Air and in Water

Playback trials using pure tones and frequency sweeps were made on Loke and Embla both in air and under water. In air, the stimulus consisted of a series of pulses, mimicking the communicative sounds made by cormorants. The stimulus was presented to the animals in different versions of filtering. The loudspeaker was positioned 1.85–6.4 m from the bird before the playback. First, a 2-kHz high-pass filtered version of the stimulus was presented to the birds at received sound levels of 54–68 dB re 20 μPa rms. The stimulus was repeated every half minute until the bird habituated to it. After habituation occurred, a second sound, usually a 500-Hz low-pass filtered version of the pulsed sequence was played to the bird at received levels of 57–67 dB re 20 μPa rms. The bird reacting (dishabituating) to the second sound indicated to us that the bird had detected this signal. Each playback experiment was filmed for documentation. Playback in water was made using an underwater loudspeaker. Tones of 500 ms duration were used with center frequencies of 2 and 8 kHz. Also, frequency-modulated upsweeps having a bandwidth of 200 Hz at 2 kHz and 800 Hz at 8 kHz were used. The behavior of the bird was monitored using an in-air video camera monitoring the large pool. When the bird was below the water, playback was made and the response of the bird was monitored. The water depth was 1 m, and the loudspeaker was situated on the bottom halfway down the long side of the pool. The received levels under water was 132–139, 143–146, 136–144, and 142–147 dB re 1 μPa rms for the 2- and 8-kHz constant frequencies and 2- and 8-kHz upsweeps, respectively.

3 Results

3.1 Psychophysical Measurements and ABR

Figure 61.2a, b shows the derived hearing sensitivity of the great cormorant in air and in water, respectively. In water, the sensitivity was restricted to a more narrow frequency band than in air. The false alarm rate was 13 and 15% and the hit rate was 69 and 72% in the in-air and underwater trials, respectively. The spread in the thresholds was 17–22 dB in air and 10–20 dB under water. The ABR sensitivities were ~10 dB higher than the behavioral thresholds at 4 and 6 kHz, whereas at 1 and 2 kHz, they were up to 40 dB lower. Figure 61.2c compares the in-air and underwater hearing thresholds by recalculating them into units of energy. The threshold values in air and in water were not significantly different ($P<0.05$) at 4.5 and 6 kHz, whereas at 2 kHz, the underwater threshold was significantly lower than the in-air threshold ($P>0.05$).

3.2 Behavioral Responses to In-Air and Underwater Playback Trials

To supplement the psychophysical measurements, we used a habituation-dishabituation design, habituating the birds with regularly occurring sudden onset sounds well within their hearing range followed by test sounds. In 5 of 10 playbacks, Loke reacted to the initial 2-kHz high-pass filtered stimulus (habituation stimulus) presented at a received level of 54–66 dB re 20 μPa rms. In 2 of the 5 habituated

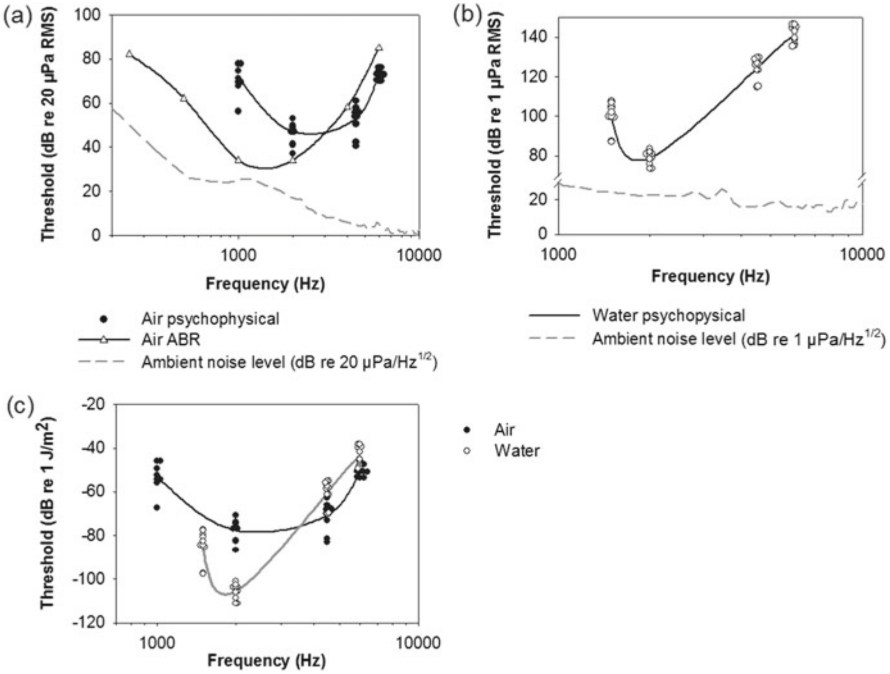

Fig. 61.2 Audiogram of a great cormorant in air (**a**) and underwater (**b**). *Gray line*, ambient-noise level. (**c**) In-air and underwater hearing thresholds compared in units of energy density. *ABR* auditory brainstem response

playbacks, Loke showed reactions to 500-Hz low-pass filtered pulses presented at 59–67 dB re 20 µPa rms (i.e., these stimuli were above hearing threshold). In 2 of 6 trials, Embla reacted to the dishabituating pulse series low-pass filtered at 500 Hz with received levels of 57–67 dB re 20 µPa rms.

For the underwater playback trials, the birds did not react to playbacks of a 2-kHz stimulus (5 trials). A playback stimulus of 8 kHz (5 trials), however, gave one clear reaction of the diving bird.

4 Discussion

Even though these findings are preliminary, they strongly suggest that the great cormorant is able to hear sound both in air and under water. Sensitivity to sound in birds is usually related to the size of the bird (Fay 1988). The in-air sensitivity in cormorants, however, is lower than that in other similar-size birds, even though the frequency range is much the same (Fay 1988). It may very well be that the behavioral sensitivity of the bird is masked by ambient noise at the lower frequencies.

However, masking is known to occur in many bird species if the spectral noise level is within 20–25 dB from the measured hearing threshold (Dooling et al. 2000). In the measurements presented here, the ratio between the measured threshold and spectral noise level is ~40–50 dB at 1 and 2 kHz, so if the thresholds here are masked, they most likely are masked only to a minor extent. The derived underwater hearing thresholds are 61–132 dB above the spectral noise levels, indicating that these thresholds are not masked by ambient noise. These thresholds are high compared with many marine-adapted mammals such as seals and whales. However, they are at the same order of magnitude as some aquatically adapted reptiles such as crocodiles and turtles (Manley 2000; Christensen-Dalsgaard et al. 2012).

The results presented here are subject to a whole series of errors. The sound field around the bird was not completely even, and the particle motion in the underwater trial was somewhat larger than that of free-field conditions. Also, the experiments were made outdoors and not in a soundproof booth so that the ambient-noise levels were constantly varying. Apart from all these problems and looking at the within-trial variation in the derived thresholds, we estimate the error in the derived thresholds to be within 2–7 dB (±1 SD) for the in-air trials and 4–7 dB for the underwater trials, with more variation at the higher frequencies than the lower ones. Currently, work is being done on reducing this variation in both setups to derive more accurate thresholds.

The behavioral responses to playback experiments in air clearly indicate that cormorants can hear relatively well around frequencies of human speech (below 1 kHz). This may further indicate that the psychophysical data presented in Fig. 61.2a is masked by ambient noise because the playback experiments were made at received levels below the hearing threshold of 1 kHz. The underwater playback experiments did not show any reliable reactions to sound, but this may be because the experimental paradigm used here was not optimal to detect reactions. Despite the errors, the results clearly show that even though cormorants do not seem to have very sensitive hearing either in air or in water, their underwater hearing is better than what would be expected from a purely in-air adapted ear (Fig. 61.2b, c). Hearing in water may be used by the cormorant to pinpoint the direction to prey, to avoid predators, and to orient underwater. More work is obviously needed to obtain more accurate hearing data on this species and to better understand the importance of underwater sounds for this and other marine birds. Such information can also be used to better understand how marine birds are vulnerable to man-made noise and if underwater sounds can efficiently be used to deter cormorants and other birds from fishing operations.

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Chapter 62
Stress Response and Habituation to Motorboat Noise in Two Coastal Fish Species in the Bothnian Sea

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Abstract The effect of motorboat noise on stress responsiveness in Eurasian perch and roach was tested in field enclosure experiments. Perch showed elevated cortisol levels after one 30-min noise exposure but not when exposed to noise repeatedly for 11 days. Roach had higher cortisol levels when exposed to noise than without noise when short- and long-term experiments were pooled. Both species had more cortisol in enclosures with mixed species compared with single-species enclosures. Both species also had higher cortisol levels in the short-term compared with the long-term experiment. Thus, a stress effect of motorboat noise may decrease with time due to habituation.

Keywords Cortisol • Eurasian perch • Roach • Sound disturbance

1 Introduction

Anthropogenic noise has, in many cases, been shown to have negative impacts on fish. For example, Engås et al. (1996) found a reduced abundance of cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus*) after seismic air gun shootings. It has also been shown that car ferries can cause changes in bluefin tuna (*Thunnus thynnus*) movement (Sara et al. 2007). Moreover, both seismic air gun noise and boat engine noise can temporarily cause hearing threshold shifts in fish

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(Scholik and Yan 2002; Popper et al. 2005). The amount of noise produced by human activities has increased not only in coastal areas but also in the deep oceans (Andrew et al. 2002; McDonald et al. 2006). Military sonar testing, pile driving, and seismic exploration produce acute high-intensity sounds, whereas different kinds of boats and vessels produce chronic low-frequency sounds (Slabbekoorn et al. 2010). Furthermore, the popularity of recreational boating activities in coastal areas is increasing, and consequently, so is the noise from their motors (Graham and Cooke 2008).

Noise-induced stress responses have been studied in several fish species. Smith et al. (2004) revealed a spike in plasma cortisol levels in goldfish (*Carassius auratus* L.) within 10 min of being exposed to computer-generated white noise (160–170 dB re 1 μPa). An increase in blood lactate and hematocrit levels has also been revealed in European sea bass (*Dicentrarchus labrax*) and gilthead sea bream (*Sparus aurata*) after noise exposure (0.1- to 1-kHz linear sweep; 150 dB root-mean-square [rms] re 1 μPa; Buscaino et al. 2010). When exposed to a stressor, fish first react with a non-specific endocrine response (Barton 2002). It involves a change in endocrine function with a release of corticosteroids and catecholamine hormones. In teleost fish, cortisol is the main corticosteroid (Sangalan et al. 1971; Hanson and Fleming 1979), and it is produced and released first after several minutes. This enables the measurement of hormone resting levels in fish without the effects of physical stressors, such as handling and capture (Gamperl et al. 1994). Studies have shown that several stressors can have a cumulative effect on fish (Barton et al. 1986). However, with repeated exposure, the stress reaction can become weaker (Clayton and Hinde 1968) because of, for example, exhaustion of the endocrine system during prolonged hyperactivity (Hontela et al. 1992) or because of habituation (Barton et al. 1987).

Most research on the effect of motorboat sound on fish has occurred in the laboratory (e.g., Graham and Cooke 2008) or used playback sounds (Picciulin et al. 2010), but it is important to evaluate how free-swimming fish in the wild respond to such commonly occurring stressors such as the noise from boats.

In this field experiment, we looked at the stress response in coastal fish exposed to motorboat sound in enclosures placed in the natural environment. The study organisms were Eurasian perch (*Perca fluviatilis*) and roach (*Rutilus rutilus*). Both species are very common in the brackish waters of the Bothnian Sea. The aim of this study was to answer the following questions:

- Does noise from motorboats cause a stress response (elevated cortisol levels) in perch and roach?
- If so, does this response last over time or can the fish become habituated when exposed to noise repeatedly?
- Is there an interspecific influence on the stress response, with perch and roach responding differently in single-species and mixed-species shoals?

The sound was produced by a recreational boat with an outboard engine, anchored in a stationary position 10 m from the enclosures. To evaluate the potential habituation effect, we exposed perch and roach to the sound either on one occasion only or twice a day for 11 days. In addition, fish were placed in either single-species or mixed-species enclosures to check for interspecific effects during the long-term experiment. The stress response was measured as whole body cortisol level.

2 Materials and Methods

The study was performed as enclosure experiments in a coastal location outside Hörnefors, Sweden (63°37′ N, 19°54′ E). The enclosures were placed in an inlet of the Bothnian Sea where boat traffic is almost absent. The experiments lasted from July to August 2011. Two sites were used to study the stress response in fish: one site with only ambient background noise and another site with experimentally controlled sound from an outboard engine. The two sites were separated by ~350–400 m, and the water depth was 3.5–4.0 m. The enclosures (1.5 × 1.5 × 1.0 m) were mounted on a floating pontoon, 3 at each site. A recreational boat (aluminum hull) with a 70-hp 4-stroke outboard motor was used as the noise source. It was placed with the bow facing the floating pontoon and the motor facing away from it. A 500-kg anchoring rig allowed stationary operation of the boat at 10.0 m from the perch enclosure, 11.5 m from the roach enclosure, and 13.0 m from the mixed-species enclosure. Both sound pressure and particle acceleration were measured. The particle acceleration measurements were performed with sound equipment developed by the Department of Meteorology at Stockholm University and the Swedish Defence Research Agency. Ambient-sound measurements were carried out at both sites in front of the floating pontoon. Additional measurements of sound from the recreational boat, with the outboard engine placed in forward gear at 2,000 rpm, were made to get the experimental sound levels in the enclosures.

Perch and roach were caught with a beach seine net in Lake Ängersjön located near Umeå, Sweden. The fish were held for 2 weeks at the Umeå Marine Science Centre in 1.0-m^3 tanks with continuously running water at natural temperatures to get them acclimatized to the brackish environment that was similar to the experimental site. The fish were fed daily with chironomid larvae. The wet mass was 13.8 ± 3.3 g (mean ± SD) for perch and 12.6 ± 9.1 g for roach.

2.1 Experimental Procedure

For the long-term experiment, ten individuals of either perch or roach were randomly chosen and placed into each of the two single-species enclosures. Additionally, five individuals of each species were placed in the mixed-species enclosures. Fish were fed twice a day with defrosted chironomid larvae (15% of total body weight/enclosure) for 11 days. Before feeding started at the noise-exposed site, the engine was started, put into gear, and run at 2,000 rpm. Every feeding session lasted for 30 min, with the food ration divided into 5–6 portions. Noise exposure occurred only during feeding. Fish at the control site were also offered food for 30 min but were not exposed to motorboat noise. The long-term noise-exposure experiment was conducted twice (with starts on 25 July and 15 August).

In the short-term experiment, ten individuals of either perch or roach were placed in each of the single-species enclosures and then left to adjust for 2 days (30 August). They were then exposed (or not exposed at the control site) to the motorboat noise once for 30 min during feeding in the same way as in the long-term experiments.

At the end of each experimental run, directly after their usual experimental treatment, fish were collected from the enclosures and killed with an overdose of MS-222. Afterward, they were transported on ice to the Umeå Marine Science Centre (10 km by car). The fish were weighed and measured before being put into a −70 °C freezer until further analysis. Only fish caught within 5 min were used in the cortisol analysis to avoid problems with capture-induced stress. The entire fish was homogenized in a volume of phosphate-buffered saline (PBS) equivalent to the fish body mass. Ethyl acetate was added (5× body mass) to the fish homogenate and the ingredients were centrifuged at 2,000 rpm for 5 min. The supernatant was used for fractionation with thin-layer chromatography (TLC). Finally, the concentration of cortisol was analyzed with radioimmunoassay (RIA; method described in Ruiz-Gomez et al. 2011).

2.2 Statistical Analysis

Cortisol data from the long-term experiment were pooled because there were no significant differences between the two experimental rounds. The data was Box-Cox transformed to meet the assumption of normal distribution and homogeneity of variance (nontransformed data are shown in the graphs). Differences in cortisol levels (in ng/g fish) between control and noise-exposed fish, for the short- and long-term experiments separately, were analyzed with an independent sample *t*-test. Differences in cortisol levels between short- and long-term exposed fish were analyzed with a two-way ANOVA (time and exposure as fixed factors). A two-way ANOVA was also run to evaluate the interspecific influence on stress levels, with treatment (single- and mixed-species enclosure) and exposure as fixed factors. IBM SPSS 21 and Statistica v. 10 (StatSoft, Inc.) were used for the statistical analyses. Particle acceleration and sound pressure were analyzed in MATLAB r2008b signal processing software (MathWorks).

3 Results

3.1 Acoustic Stimuli

The sound pressure level was measured to 147 dB re 1 μPa (frequency range: 150–5,000 Hz) at the floating pontoon situated 10 m away from the outboard engine. The particle acceleration was 9.7×10^{-3} m/s^2 rms at the perch enclosure, 8.6×10^{-3} m/s^2 rms at the roach enclosure, and 7.8×10^{-3} m/s^2 rms at the mixed-species enclosure. The ambient background noise in terms of particle acceleration was 1.5×10^{-5} m/s^2 rms measured in the frequency range of 10–300 Hz.

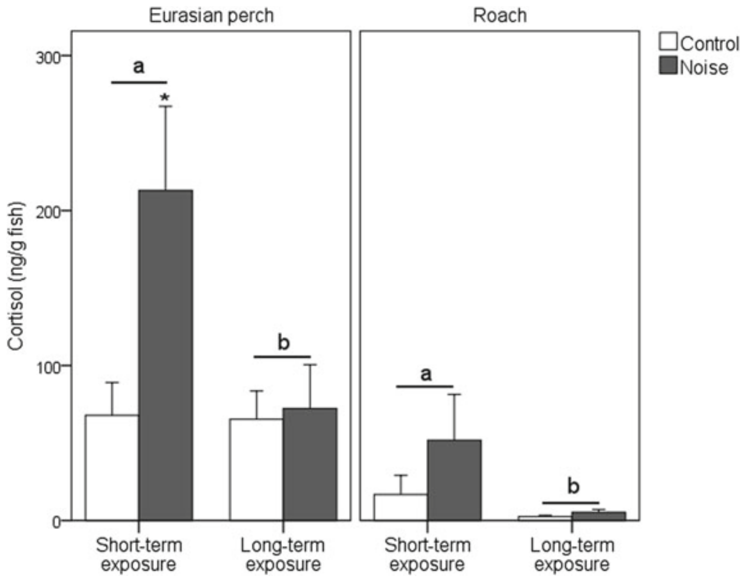

Fig. 62.1 Mean (+ SE) cortisol concentration in Eurasian perch and roach subjected to either noise or no noise (control) in short- and long-term experiments. Significant difference in cortisol levels: *, between treatments (noise and control; *t*-test): *a* and *b*, between short- and long-term experiments (two-way ANOVA)

3.2 *Effects of Noise Exposure and Time*

In the short-term experiment, noise-exposed perch had significantly higher cortisol levels than individuals in the control group (*t*-test: $t=-2.28$, df$=17$, $P=0.036$; Fig. 62.1). In the long-term experiment, noise exposure had no significant effect on the cortisol levels of perch (single-species enclosure; *t*-test: $t=0.63$, df$=27$, $P=0.54$). When the short- and long-term experiments were compared, there was a significant difference in the cortisol levels for perch (two-way ANOVA, time effect: $F_{1,44}=4.844$, $P=0.033$), with fish from the short-term experiments having higher cortisol levels. No overall effect of noise exposure was found (exposure effect: $F_{1,44}=1.82$, $P=0.18$). The interaction term, however, was significant (time × noise exposure: $F_{1,44}=4.61$, $P=0.037$), with a significant difference in the cortisol levels for noise-exposed perch between the two experimental setups, that is, the short- and long-term experiment (least significant difference post hoc, $P=0.005$).

Noise exposure had no significant effect on the cortisol levels of roach in the short-term experiment (*t*-test, $t=-0.99$, df$=16$, $P=0.34$; Fig. 62.1). In the long-term experiment, the results were similar, with no significant effects of noise exposure on roach (single-species enclosure: *t*-test, $t=-1.76$, df$=31$, $P=0.088$) but with a tendency for higher cortisol levels at noise exposure. When the short- and long-term experiments were compared, roach from the short-term experiment had significantly

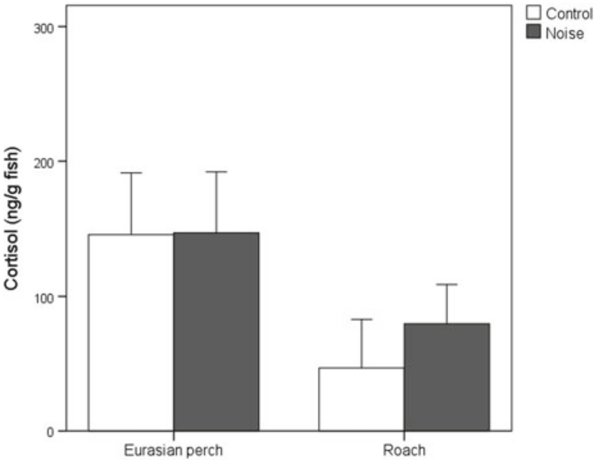

Fig. 62.2 Mean (+ SE) cortisol concentration in Eurasian perch and roach kept in mixed-species enclosures subjected to either noise or no noise (control)

higher cortisol levels than roach from the long-term experiment (two-way ANOVA, time effect: $F_{1,47}=4.41$, $P=0.041$). The overall effect of noise exposure was close to significant (exposure effect: $F_{1,47}=3.53$, $P=0.066$), with higher cortisol levels in noise-exposed individuals than in the control group and a nonsignificant interaction term (time × noise exposure: $F_{1,47}=0.01$, $P=0.97$; Fig. 62.2).

3.3 Effects of Species Mixture and Noise Exposure

Noise exposure alone had no significant effect on the cortisol levels of perch in the mixed-species enclosure (mixed-species enclosure: *t*-test: $t=-0.45$, df = 11, $P=0.66$). When the single- and mixed-species enclosures were compared, perch from the mixed-species enclosures had higher cortisol levels than perch from the single-species enclosures (two-way ANOVA, enclosure effect: $F_{1,38}=5.31$ $P=0.027$). In addition, the analysis showed no overall effect of noise exposure (exposure effect: $F_{1,38}=0.04$, $P=0.95$), with no significant interaction (enclosure × noise exposure: $F_{1,38}=0.54$, $P=0.47$).

Noise exposure alone had no significant effect on the cortisol levels of roach in the mixed-species enclosures (mixed-species enclosure: *t*-test, $t=-1.57$, df = 15, $P=0.14$). When the single- and mixed-species enclosures were compared, roach from the mixed-species enclosures had higher cortisol levels than roach from the single-species enclosures (two-way ANOVA, enclosure effect: $F_{1,46}=10.73$, $P=0.002$). The overall effect of noise exposure was significant, with higher levels of cortisol for noise-exposed roach than for control fish (exposure effect: $F_{1,46}=6.07$, $P=0.018$). The interaction term was not significant for roach (enclosure × exposure: $F_{1,46}=0.453$, $P=0.50$).

4 Discussion

4.1 *Effects of Noise Exposure and Time*

Perch had elevated cortisol levels after being exposed once to 30 min of motorboat noise when acclimated to the enclosures for 2 days (short-term experiment). After repeated noise exposure (long-term experiment), there were no such differences between noise-exposed and control fish. Cortisol levels were also significantly lower in noise-exposed perch from the long-term experiment than in individuals subjected to noise only once. This suggests that the perch can become habituated if exposed to noise repeatedly. Our results are consistent with previous results on handling stress in perch where repeatedly handled individuals produced less stress hormones than individuals subjected to handling for the first time (Jentoft et al. 2005). From our study, it is also evident that habituation can be rapid for perch because the experiment lasted for only 11 days. However, the connection between noise and feeding might have enhanced the habituation process.

Roach did not respond with elevated cortisol levels after 30 min of noise exposure nor after repeated noise exposure, although there was a tendency for higher cortisol levels compared with the control fish. Also, the results from the test of species mixture show that noise disturbance can be important even after 11 days (overall effect of noise disturbance, single and mixed combined). The variance in cortisol levels among roach individuals was high, and the overall significant effect of noise when comparing the two species treatments suggested that a larger sample size would have been beneficial. Furthermore, a comparison of the short- and the long-term experiments revealed a significant effect of time. Roach from the short-term experiment had higher cortisol levels than roach from the long-term experiment irrespective of noise exposure. This could be due to a habituation effect. Alternatively, the general elevated cortisol levels in the short-term experiment may be explained by an insufficient time for acclimation in roach. For example, a previous study on cichlids showed that 3-4 days may be required (Wong et al. 2008).

4.2 *Effects of Species Mixture and Noise Exposure*

Alone, noise exposure had no significant effect on either perch or roach in the mixed-species experiment. However, species mixture in itself was important for both species. Both perch and roach showed elevated levels of cortisol in mixed enclosures. Perch and roach commonly coexist, competing for food or with a predator–prey relationship depending on size differences (e.g., Persson 1988). The coexistence in an enclosed space may therefore cause stress. Consequently, interspecific influences might be of importance for stress levels in fish and may also give a cumulative effect together with noise and other stressors (cf. Barton et al. 1986).

4.3 Conclusions

The results of this study indicate that both perch and roach respond to motorboat sound with a stress response in terms of elevated cortisol levels. The strongest response was seen in perch subjected only once to the motorboat noise, but even roach showed tendencies in the same direction. Perch showed signs of habituation to the noise, with no differences between noise-exposed and control fish in the long-term experiment. The effect of the presence of the other species in terms of increased cortisol levels, which was found in both perch and roach, also showed that many different stressors may influence the performance of a fish in the natural habitat. Our study is one of the few that has studied the effect of boat noise in a natural habitat (but see Picciulin et al. 2010) and with a natural sound source rather than recorded playback sounds. Field experiments are important to get realistic effects on the disturbance from the increasing boat traffic on fish, and more studies in the wild are needed.

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Chapter 63
Cumulative Effects of Exposure to Continuous and Intermittent Sounds on Temporary Hearing Threshold Shifts Induced in a Harbor Porpoise (*Phocoena phocoena*)

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Abstract The effects of exposure to continuous and intermittent anthropogenic sounds on temporary hearing threshold shifts (TTSs) in a harbor porpoise were investigated by testing hearing before and after exposure to 1- to 2-kHz downsweeps of 1 s, without harmonics, presented as paired-intermittent and continuous-exposure combinations with identical cumulative sound exposure levels ($\mathrm{SEL_{cum}}$). Exposure to intermittent sounds resulted in lower TTSs than exposure to continuous sounds with the same $\mathrm{SEL_{cum}}$. Therefore, the hearing of marine mammals is at less risk from intermittent anthropogenic noises than from continuous ones at the same received sound pressure level and duration.

Keywords Anthropogenic sound • Recovery of hearing • Naval sonar • Odontocetes • Pile driving • Seismic surveys

1 Introduction

Marine mammals use sound for activities such as orientation, communication, predator avoidance, and foraging. Some anthropogenic sounds may interfere with these activities by masking the sounds, distracting the animals, or temporarily or permanently reducing an animal's hearing. Sound may also displace animals from ecologically important areas. To prevent hearing reduction, regulators allow the activities of construction companies to be conducted only when mitigation measures such as constructing only seasonally, limiting the total duration, and using technical adaptations such as a soft and slow start in the case of pile driving are

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used. In some countries, the regulators set criteria for the maximum levels of certain anthropogenic sounds to which marine mammals can be exposed. Cumulative sound exposure level ($\mathrm{SEL_{cum}}$) is one way to quantify sound exposure and is used so that criteria can be set to prevent temporary hearing threshold shift (TTS) and permanent hearing threshold shift (PTS).

Research on TTS in odontocetes has been focused mainly on exposure to single impulsive sounds or continuous sounds (Finneran et al. 2000, 2002, 2010a; Kastelein et al. 2012a), and little is known about the cumulative effect of exposure to intermittent sounds. Many anthropogenic noises are intermittent (e.g., sonar signals and sounds produced during pile driving and seismic air gun surveys). Predicting the TTS induced by exposure to these sounds is difficult. Finneran et al. (2010b) measured TTS in a bottlenose dolphin (*Tursiops truncatus*) exposed to a sequence of four tones separated by periods of silence (duty cycle ~7%). The resulting TTS (growth and recovery) was compared with TTS in the same animal exposed to single continuous tones with a similar $\mathrm{SEL_{cum}}$ and with a single tone with a similar sound pressure level (SPL) and equal duration to a single tone in the sequence of four. The data showed the potential for accumulation of TTS from multiple exposures and for recovery of hearing during the quiet intervals between exposures. Mooney et al. (2009) also studied TTS in bottlenose dolphins and suggested that intermittent exposures might require a higher $\mathrm{SEL_{cum}}$ to induce TTS than continuous exposures.

Bottlenose dolphins exposed to continuous sounds have recovery rates of ~0.25 dB/min for thresholds shifts of ~3 dB (Finneran et al. 2005). For harbor porpoises (*Phocoena phocoena*), initial recovery rates (i.e., within 8 min after the fatiguing noise stopped) of ~0.25 dB/min have been reported for TTSs ranging from 10 to 14 dB (Kastelein et al. 2012a). These recovery rates suggest that the TTS induced by multiple intermittent exposures is negatively correlated to the time between exposures, during which the hearing may recover from preceding exposures.

The rate at which many intermittent anthropogenic sounds are produced can, in principle, be adjusted by the operators (e.g., pile-driving rates, seismic survey rate, sonar rates), so there is potential to reduce their impact on the hearing of marine mammals. Research on the intermittence of potentially harmful sounds is valuable for regulators because it may allow criteria for SELs to be set to minimize their impact on marine life. The goal of the present study was to investigate the cumulative effects of continuous and intermittent sound exposures on the TTS induced in a harbor porpoise.

2 Materials and Methods

A harbor porpoise was exposed to 1- to 2-kHz downsweeps of 1 s, without harmonics, presented as intermittent and continuous exposures. The study animal, area, and methodology were described by Kastelein et al. (2012a). The 1- to 2-kHz downsweep (for details see Kastelein et al. 2012b) was used as fatiguing noise because this study was executed during a larger TTS study regarding the effects of

Table 63.1 Exposure parameter combinations

		Continuous condition	Intermittent condition, 60-min exposures	
Exposure parameter combination	SEL_{cum}, dB re 1 μPa²·s	Duration, min	Interpulse interval, s	Duty cycle, %
1	202	60	0	100
2	201	45	0.3	75
3	199	30	1	50
4	198	22.5	1.7	37.5
5	196	15	3	25
6	195	10.5	4.7	17.5
7	192	6	9	10
8	189	3	19	5

The exposure parameter combinations resulting in eight cumulative sound exposure levels (SEL_{cum}) for the two exposure conditions (continuous and intermittent). Mean sound pressure level was 168 ± 2.5 dB re 1 μPa for both conditions. For exposure parameter combination 1, the continuous and intermittent conditions were identical

low-frequency active naval sonar signals (LFASs) on harbor porpoise hearing. Two fatiguing exposure conditions were examined: continuous and intermittent. Exposure combinations in the continuous and intermittent conditions were paired so that the continuous condition contained an exposure parameter combination that created the same SEL_{cum} as an exposure parameter combination in the intermittent condition. This resulted in eight exposure parameter combinations per exposure condition (Table 63.1). For both conditions, the mean received SPL, from the power-based sum of all the measurement points in the pool, was kept constant at 168 ± 2.5 dB re 1 μPa (as the animal swam throughout the entire pool during the sound exposure periods). For the continuous condition, the duration of sessions was variable, and for the intermittent condition, the duty cycle was variable while the duration of the session was kept constant at 60 min. All exposure parameter combinations for each condition were only tested once.

A linear upsweep centered at 1.5 kHz (starting and ending at ±2.5% of the center frequency), with a duration of 1 s (including a linear rise and fall in amplitude of 50 ms), was used as the hearing test signal that the animal was asked to detect before and after exposure to the fatiguing noise. The 1.5-kHz signal was used because Kastelein et al. (2013) showed that the harbor porpoise is more affected by TTS at the center frequency of the fatiguing noise than at higher frequencies when a continuous tone is used as fatiguing noise.

One total noise exposure test consisted of (1) a baseline hearing test, (2) noise exposure, and (3) a postnoise exposure hearing test during the first 4 min after the fatiguing sound had stopped.

A psychophysical technique was used to measure the porpoise's hearing. Each hearing test trial began with the animal at the start/response buoy. The level of the hearing test signal used in the first trial of the session was ~6 dB above the hearing threshold that was determined during the previous session. When the trainer gave a hand signal, the porpoise was trained to swim to the listening station. The methodology was as described by Kastelein et al. (2012b). The signal level was varied according to the one-up/one-down adaptive staircase method. This conventional psychometric technique can produce a 50% correct detection threshold. Steps of 2 dB were used. During signal-present hearing test trials, the porpoise stationed and waited for a random period of between 6 and 12 s (established via a random number generator) before the signal operator produced the test signal. A switch from a test signal level to which the porpoise responded (a hit) to a level to which he did not respond (a miss) and vice versa was called a reversal.

Each complete hearing session consisted of ~12 trials and lasted for up to 4 min. A session was only used in the analyses if four reversals were obtained. Sessions consisted of 2/3 signal-present and 1/3 signal-absent trials offered in a quasi-random order. There were never more than three consecutive signal-present or signal-absent trials. The $TTS_{1\text{-}4}$ was calculated by subtracting the mean baseline hearing threshold from the mean hearing threshold 1–4 min after the fatiguing sound had stopped.

3 Results

Figure 63.1 shows that the mean $TTS_{1\text{-}4}$ caused by a 168 dB re 1 µPa SPL exposure to variable duration sequences of continuous sounds varied between 4 and 30 dB. The $TTS_{1–4}$ for sequences of sounds with constant exposure durations (i.e., 60 min) but variable duty cycles varied between 0 and 27 dB. Exposure to intermittent sounds resulted in lower TTSs than exposure to continuous sounds with the same SEL_{cum}.

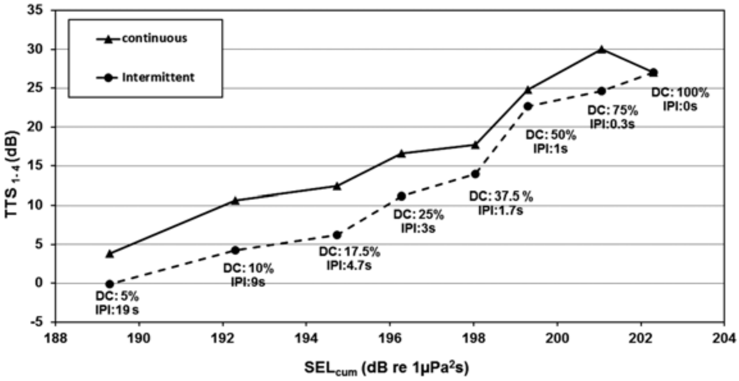

Fig. 63.1 The mean temporary threshold shift (TTS) quantified 1–4 min after sound exposure stopped ($TTS_{1–4}$) in a harbor porpoise for 60-min sequences of intermittent sounds (interpulse intervals [IPIs] ranging from no interval to a 19-s interval, resulting in duty cycles [DCs] ranging from 5 to 100%) and for continuous sounds of variable length (1.5–60 min; 100% duty cycle). Continuous and intermittent conditions are paired as eight exposure parameter combinations, which contain variable numbers of sounds (1-s sweeps), resulting in the same cumulative sound exposure levels (SEL_{cum}). Mean exposure sound pressure level was 168 dB re 1 µPa

4 Discussion

Although based on one harbor porpoise, the results show that exposure to intermittent sounds results in lower TTSs than exposure to continuous sounds with the same SEL_{cum}. Therefore, the hearing of marine mammals is at less risk from intermittent anthropogenic noises than from continuous ones (at the same received SPL and exposure duration). Several factors may contribute to this lower TTS; intermittent exposures may allow the ear to recover during the intervals or may result in different stresses on the cochlear structures than continuous exposures. In the present study, a 19-s interpulse interval (IPI) resulted in no measurable TTS. However, Finneran et al. (2010b) reported that tones of 16 s with an IPI of 224 s and an SPL of ±192 dB re 1 μPa resulted in a significant TTS (7.2 dB) in a bottlenose dolphin. Finneran et al. (2010b) found that exposure to intermittent and continuous sounds with the same SEL_{cum} resulted in differences in TTS similar to the results in the present study for IPIs above 3 s. The difference between continuous and intermittent exposures with the same SEL_{cum} in both studies is ~5 dB.

To understand more fully the effects of intermittence and to make models to predict TTS from intermittent noise exposures, more data are needed, as pointed out by Finneran et al. (2010b), but the present study provides insight into the cumulative effect of intermittent exposures. In harbor porpoises, as in bottlenose dolphins (Finneran et al. 2010b), exposure to intermittent sounds results in smaller TTSs than exposure to continuous sounds with the same SEL_{cum}. These results can be used to reduce the risk of hearing loss in marine mammals due to anthropogenic noise.

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Chapter 64
Great Ears: Low-Frequency Sensitivity Correlates in Land and Marine Leviathans

D.R. Ketten, J. Arruda, S. Cramer, and M. Yamato

Abstract Like elephants, baleen whales produce low-frequency (LF) and even infrasonic (IF) signals, suggesting they may be particularly susceptible to underwater anthropogenic sound impacts. Analyses of computerized tomography scans and histologies of the ears in five baleen whale and two elephant species revealed that LF thresholds correlate with basilar membrane thickness/width and cochlear radii ratios. These factors are consistent with high-mass, low-stiffness membranes and broad spiral curvatures, suggesting that Mysticeti and Proboscidea evolved common inner ear adaptations over similar time scales for processing IF/LF sounds despite operating in different media.

Keywords Low frequency • Hearing • Whales • Impacts

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1 Introduction

Recently demonstrated sound impacts on multiple marine species and habitats have produced growing concerns and intensified oversight of commercial-, military-, and research-related human activities in the ocean. Despite these concerns and increased media attention as well as substantive increases in fundamental and applied research on marine hearing, there continues to be a paucity of data on many marine species. Most notably, there is a lack of data on baleen whales (Mysticeti), which, as the largest cetaceans, are the marine taxa with the greatest probable sensitivity to low frequencies and thus are the species most likely to be impacted by the majority of anthropogenic contributions to ocean noise.

1.1 Current Data Gaps and Challenges

In land mammals, we have extensive data on the electrophysiological, mechanical, and morphological substructure of hearing. We know that mammals differ in their absolute frequency ranges and that these differences correlate with the morphology of some elements. For most mammals, detailed hearing data are obtained by acute experiments or behavioral tests. In cetaceans (dolphins and whales), however, we have remarkably few data considering the number and diversity of whale species. Less than 15% of all cetacean species have been tested behaviorally or physiologically, and all such data to date were obtained from smaller odontocetes (toothed whales, dolphins, and porpoises), all of which are ultrasonic echolocators. Although data on baleen whales are needed most urgently, these are also the animals least approachable by conventional audiometric methods. Mysticetes have not been held for any protracted time in captivity and they seldom strand live. Furthermore, they are unlikely to be tested successfully by current auditory brainstem response (ABR) or auditory evoked potential (AEP) techniques. At present, for reliable results, both techniques require that the brain mass-to-body mass ratio be similar or greater than that of humans (~1.5%) or that the tissues monitored be relatively close to the electrode sites. As head mass increases, the auditory centers must therefore be relatively large compared with the rest of the brain and near the surface electrode placement to produce a sufficiently strong signal detectable without corruption by myogenic, neural, or other conflicting activity. Consequently, ABR methods work well on smaller cetaceans, particularly if trained to station while undergoing testing, but these methodologies are not viable for baleen whales that have a brain-to-body mass ratio of 0.01%, i.e., two magnitudes smaller than that of most toothed whales (~2%; Ridgway and Wood 1988; Marino et al. 2006). Therefore, it is important to explore alternative methods for obtaining reliable underwater hearing and impact estimates for these large and, in some cases, critically endangered whales.

There is an additional aspect to mysticetes and their terrestrial proboscidean counterparts that makes investigation of their hearing useful for the field of auditory sciences in general. Playbacks and recordings of vocalizations indicate that all proboscideans and mysticetes produce and respond to low-frequency (LF) or even infrasonic (IF) signals (Payne et al. 1986; Langbauer et al. 1991; Wartzok and Ketten 1999). Whales operate with a 4.5-fold increase in sound speed and a 3-magnitude (3,600 times higher) differential in specific acoustic impedance compared with elephants. There is also a commonly held tenet that hearing limits are correlated with body mass. Were these expectations all true, there should be virtually no overlap in the hearing of these two taxa. Yet we know that there are both limits as to what can be heard by any species based on the intersection of the physics of sound, habitat, and the species ancestral auditory "warehouse." Recordings of vocalizations and behavioral observations suggest that hearing in Mysticeti and Proboscidea converged to function well at low-to-seismic signal frequencies. Thus, analyses of these leviathan ears can provide insights into how a mammalian ear can be structured to receive and process exceptionally LFs, even though the signals are emitted and perceived in media (air vs. water) with significantly different physical acoustic properties.

2 Hypothesis

The goal of this study was to determine how inner ears in the largest mammals are structured for LF hearing from the gross to the cytoarchitectural level. Our basic hypothesis is that land and marine mammals have common fundamental hearing mechanisms and that there are structural inner ear elements common to marine and terrestrial species that correlate with LF versus high-frequency (HF) hearing abilities regardless of the medium in which they operate. To that end, we initiated a comparative study of the representative mysticete and proboscidean ears and compared basic inner ear morphometrics of these species with those of land and marine midfrequency (MF) and HF mammals.

3 Methods

3.1 Study Specimens

Data for MF and HF terrestrial ears were obtained from previous published studies. New data on LF proboscids, LF mysticetes, and HF odontocete species in this study were obtained through computerized tomography (CT) and celloidin histology preparations of 30 ears from 5 species of baleen whales and 2 elephant species distributed as follows: 4 Proboscidae: African elephant *Loxodonta africana* (3 CT/1 histology) and Asian elephant *Elephas maximus* (1 CT/0 histology); 16 Mysticeti: humpback whale *Megaptera novaeanglia* (6 CT/1 histology), blue whale *Balaenoptera musculus* (3 CT/1 histology); right whale *Eubalaena glacialis* (3 CT/2 histology), minke whale *Balaenoptera acutorostrata* (3 CT/2 histology), and finback whale *Balaenoptera physalus* (1 CT/0 histology); and 10 Odontoceti: harbor porpoise *Phocoena phocoena* (5 CT/5 histology), and bottlenose porpoise *Tursiops truncatus* (5 CT/5 histology).

3.2 Imaging Procedures

Specimens of whole animals, heads, and temporal bones were scanned at the Woods Hole Oceanographic Institution facility (http://csi.whoi.edu) on a Siemens Volume Zoom CT unit using the following helical scan protocol: 0.5 mm/s acquisitions, 0.5 mm collimation, and ultrahigh resolution (UHR) 90 and 95 head and body kernels, and on an X-Tek Micro CT at the Harvard University Center for Nanoscale Systems. Primary images of the inner ear labyrinth were reconstructed in the transaxial plane with a 100-μm isotropic voxel with a 50-mm field of view (FOV). Additional 2-dimensional (2-D) paramodiolar and 3-dimensional (3-D) orthogonal projections were also reformatted from the raw attenuation data for comparably oriented images for all ears. Raw attenuation data, primary transaxial images, and all 2-D and 3-D reformatted and reconstructed images were archived on magneto-optical and DVD disks. Both CT- and histology-derived digital images were reconstructed using Amira and Osirix software.

3.3 Histology Procedures

For histologic analyses, the temporal bones were decalcified in EDTA, embedded in celloidin, sectioned at 2–30 μm, and mounted on glass slides, with every tenth section stained with hematoxylin-eosin. Because of the exceptional density of mysticete periotics, the decalcification process in EDTA required 1–2 year for most specimens. For some species, more rapid decalcifications were attempted using nitric acid- and hydrochloric acid-based decalcificants, but these invariably resulted in compromised soft tissues. Similarly, paraffin embedding, which entails heating of the tissue, was found to produce substantial artifacts.

3.4 Morphometric Procedures

Cochlear radii, lengths, and basilar membrane dimensions were obtained by direct measurement with light microscopy with a calibrated reticule and 3-D mapping and calculations from 2-D CT and 3-D reconstructions following the techniques of Ketten et al. (1998). Calculations of cochlear maps employed Archimedean and equiangular spiral approximations as described by Ketten and Wartzok (1990),

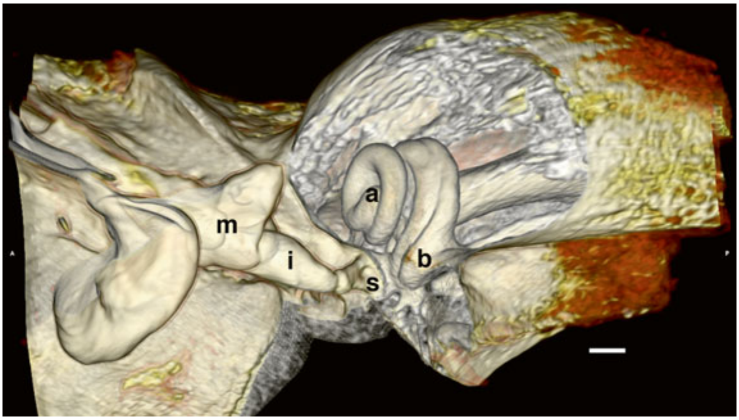

Fig. 64.1 Blue whale (*Balaenoptera musculus*) cochlear labyrinth and ossicular chain anatomy imaged in situ with 3-D multisegmented ultrahigh resolution (UHR) computerized tomography (CT). The deep groove adjacent to the basal turn label at the cochlear aqueduct is the indentation created by the outer osseous lamina. m, Malleus; i, incus; s, stapes; a, apex of cochlea; b, basal turn of cochlea. Bar = 5 mm. Printed with permission from D. Ketten, Computerized Scanning and Imaging Facility (CSI), Woods Hole Oceanographic Institution (WHOI)

Ketten et al. (1998), and Manoussaki et al. (2008). Radii ratios were calculated from measures of the basal and apical radii. In histologies, these radii can be measured from midmodiolar sections, and in CT scans, they are best measured on orthogonal 3-D reconstructions of the fluid and membranous labyrinths (Fig. 64.1). In this study, the basal radius was defined as the line subtended from the modiolar center to the inner edge of the outer osseous lamina at the juncture of the basal turn and cochlear hook. In scans, this can be seen as the laminar groove in the reconstructions of the fluid labyrinth (Fig. 64.1) and as the outer edge of the basilar membrane in micro-CT reconstructions (Fig. 64.2). The apical radius was defined as a line subtending from the modiolar center to the midpoint of the basilar membrane at the helicotrema.

Basilar membrane thickness and width dimensions were measured on radially resectioned reconstructions. Widths were determined to be the distance along the basilar membrane from the attachment point of the spiral ligament to the most prominent edge of the inner osseous laminae. The membrane thickness was measured at the midpoint of the membrane, coincident with the thickest region of the pars pectinata.

Comparisons of reconstructions and measurements from histologies and CT data for the same temporal bones demonstrated that shrinkage and compression artifacts occurred in some of the histologic material. Therefore, the histologies were used primarily to obtain basilar membrane dimensions, with CT images providing superior data for both visualization and measurement of undisturbed inner ear labyrinthine anatomy and measures of cochlear lengths, heights, and radii.

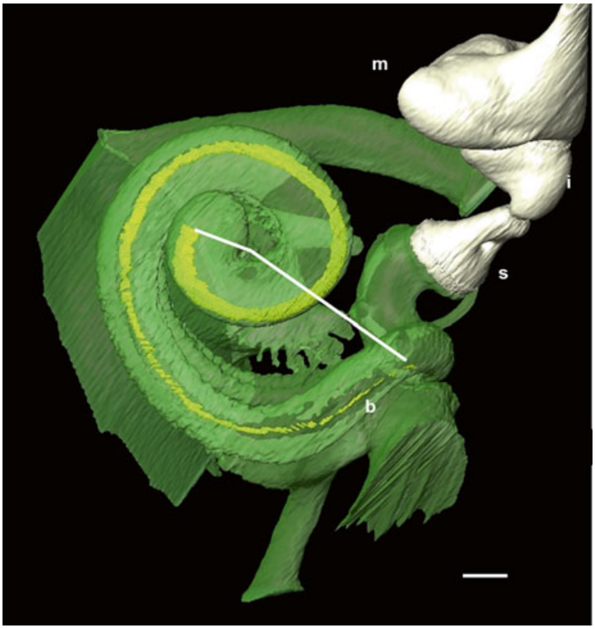

Fig. 64.2 Harbor porpoise (*Phocoena phocoena*) cochlear labyrinth and ossicular chain imaged with micro-CT at 18-μm voxel resolution. The basilar membrane position and width (*yellow*) is shown within the transparent scalae. The angled *white lines* demonstrate the positions of the apical and basal radii. Bar = 1 mm. Printed with permission from D. Ketten, CSI, WHOI

4 Results

Both the largest whales and elephants have generalist ear formats (Table 64.1, Fig. 64.1), with 2–2.5 turns and constant grading of the basilar membrane thickness and width, base to apex. There is no significant difference in the turn number among the species examined, with the exception of the highest frequency marine echolocators, notably the harbor porpoise, which has previously been shown to have a 1.5 turn cochlea with extensive, thick-walled inner and outer osseous laminae (Ketten and Wartzok 1990). Cochlear lengths are substantially greater in larger whales than in elephants but are correlated in all species with body mass rather than with LF or HF hearing limits (Fig. 64.3).

The most notable differences in the LF species examined in comparison to MF and HF species and the strongest correlates of hearing limits for both generalist and specialist ears are the basilar membrane ratios at both the base and apex of the cochlea (Fig. 64.3). The basilar membrane basal widths and thicknesses in the LF species are similar to that of a human or, in some cases, slightly narrower (120–200 μm × 5–7 μm). The apical dimensions were exceptionally broad and thin in all mysticetes and proboscids (1,100–2,200 μm × 1–2 μm) and are in distinct contrast to those of the majority of other marine and land mammals, particularly in comparison to echolocators that have basilar membrane dimensions substantially narrower and thicker at both the base (30 × 20 μm) and apex (100–400 μm × 2–5 μm). A second feature that characterized both land and marine LF species is the presence of large radii ratios ranging from >7.2 to over 10 in comparison to MF and HF species with ratios ranging from 4 to 7 (Table 64.1).

Table 64.1 Cochlear morphometry of cetacean and terrestrial mammals

Species	Common name	Animal weight, kg	Frequency range, kHz	Turns	Basilar membrane length, mm	Basal ratio, t/w	Apical ratio, t/w	Radii ratio
Phocoena phocoena	Harbor porpoise	50	0.35–180	1.5	22.5	0.833	0.0172	4.3
Tursiops truncatus	Bottlenose dolphin	155	0.15–160	2.25	39.24	0.714	0.0132	4.9
Balaenoptera acutorostrata	Minke whale	8000	0.02–35	2.25	46.86	–	–	7.2
Balaenoptera musculus	Blue whale	100,869	0.01–18	2.25	72.3	0.058	0.0009	10.5
Balaenoptera physalus	Fin whale	–	0.01–0.75	2.5	64.7	0.050	0.0010	9.8
Eubalaena glacialis	Right whale	31,837	0.016–25	2.5	56.18	0.056	0.0017	9.2
Megaptera novaeangliae	Humpback whale	30,000	0.018–30	2.0	59.61	0.056	0.0019	8.2
Bos Taurus	Cow	500	0.14–22	3.5	38.0	–	–	7.5
Cavia porcella	Guinea pig	0.5	0.2–45	4.25	18.5	0.106	0.0082	7.4
Elephas maximus	Asian elephant	4000	0.1–5.7	2.25	57.4	0.016	0.0017	8.7
Loxodonta africana	African elephant	–	0.01 to >8	2.5	65.1	0.01	0.0014	9.0
Felis domesticus	Cat	3.0	0.125–70	3.0	25.8	0.150	0.0119	5.7
Homo sapiens	Human	75	0.05–16	2.5	34.78	–	–	7.0
Mus musculus	Mouse	0.01	5–60	2.0	6.8	0.363	0.0063	4.0
Rattus norvegicus	Rat	0.2	1–59	2.2	10.7	0.300	0.0106	4.3
Spalax ehrenbergi	Mole rat	0.08	0.1–10	3.5	13.7	0.075	0.0900	–
Myotis lucifugus	Little brown bat	0.007	12.5–100	2.25	6.9	–	–	
Pteronotus parnelli	Mustached bat	0.012	25–115		14.3	0.440	0.022	4.0
Rhinolophus ferrumequinum	Horseshoe bat	0.018	30–90	3.25	16.1	0.388	0.0133	3.9

All morphometric values are averages of previously published data or as noted new data for specimens in this study. Frequency ranges for all Mysticeti and for *L. africana* are based on published vocalizations and playback responses. *t/w* thickness to width. Modified from Ketten (2000) and Wartzok and Ketten (1999)

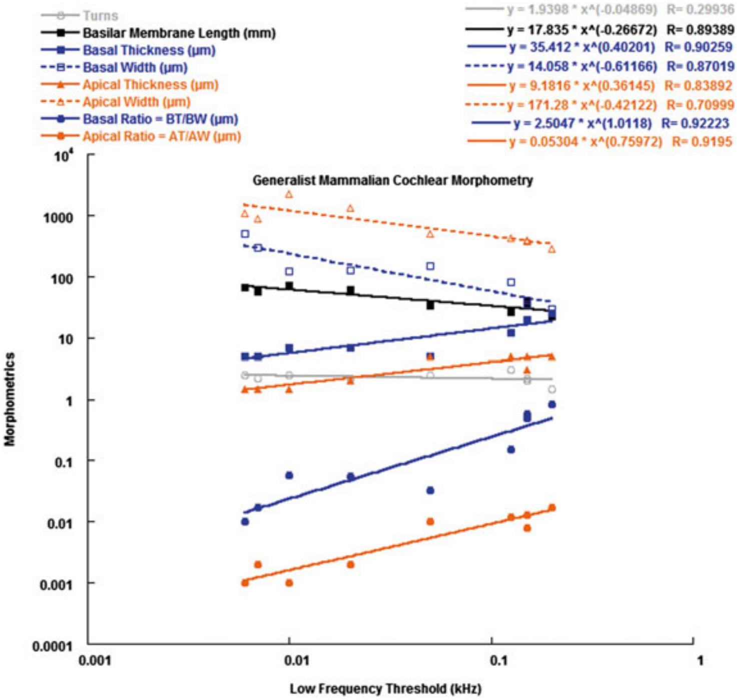

Fig. 64.3 Plot of cochlear morphometrics vs. low-frequency threshold at 60 dB re 20 μPa in air for terrestrial animals and 120 dB re 1 μPa in water for cetaceans. BT/BW, basal thickness-to-basal width ratio; AT/AW, apical thickness-to-apical width ratio

5 Discussion

5.1 *Basilar Membrane Morphometry*

All major features of the mammalian cochlear morphometry have been implicated in previous analyses of the determinants of hearing ranges by numerous authors, particularly the turn number, length, membrane dimensions, and curvature (West 1985; Greenwood 1990; Ketten and Wartzok 1990; Echteler et al. 1994). In this study, the critical features distinguishing LF ears were found to be in no single structure but were rather a proportional anatomy; i.e., basilar membrane and radii ratios. Mysticetes have larger membrane gradients and are likely to have substantially greater hearing ranges than elephants (~10 vs. 6–8 octaves). However, cochlear coiling and apical cochlear anatomies are similar across whales and elephants, suggesting common functional adaptations for improved apical LF propagation. LF sensitivity in both groups is strongly correlated with similar, exceptionally small apical basilar membrane thickness-to-width ratios. These ratios are driven by the thinness of the membrane and reflect a broad cross-sectional area that is relatively poorly invested with collagen fibers. This is in contrast to the basal regions in which there is an increase in collagen density and in even starker contrast to the basilar membrane anatomy of HF species. Basal basilar membrane development reaches an extreme in HF specialist ears like that of *Phocoena* and *Rhinolophus*, both of which have radial and longitudinal fiber complements in the basal regions as well as heavy laminar buttressing that is absent in all LF ears examined. The extremely low membrane ratios in mysticetes and proboscids, in turn, reflect substantially reduced stiffness, with conserved mass in the greater apical cross-sectional area, consistent with lower apical stiffness than that of MF and HF species (Miller et al. 2005). Some smaller LF specialist ears, like those of the mole rat (*Spalax ehrenbergi*), achieve lower resonant frequencies by adding mass to the membrane despite their relatively small, short cochlear dimensions.

5.2 Spiral Conformation

Coiling is a major feature of mammalian cochleas that is absent in nonmammalian or even primitive mammalian species such as monotremes, reptiles, and fishes, all of which have comparatively narrow hearing ranges. Consequently, it is sometimes assumed that the main function of the coiled cochlea is to conserve space while lengthening and thus increasing the resonant structures and range of the inner ear. Spiral curvature, however, can affect a number of critical biomechanical processes. In recent years, coiling has garnered increasing attention not only for its general role in increasing the hearing range of mammalian cochleas but also, considering the variability among species, for its potential as a key element of categorical (LF vs. HF) hearing abilities and even variations in hair cell response mechanisms (Steele & Zais 1985; Cai et al. 2005; Manoussaki et al. 2006). The ratio of minimum and maximum cochlear radii is strongly correlated with LF thresholds. Manoussaki et al. (2006, 2008) provided a mechanistic explanation for enhanced LF sensitivity and LF penetration to the cochlear apex as a result of spiral curvature variations that influence wave energy redistribution toward the outer wall of the scalae, in effect resulting in a biologic equivalent of the classic “Whispering Gallery” effect. Although the present study does not provide additional mechanistic insights into the role of the cochlea, the data reported here on a subset of mysticete ears are consistent with the trends in spiral morphometry and broadening of the cochlear curvature in LF-sensitive species previously reported for terrestrial species by Manoussaki et al. (2008). It is noted, however, that although the overall trends in both studies are consistent, the exact radii ratios vary in these two studies for some species. This is likely a result of relatively small sample sizes for many of the coincident species in both studies.

The data presented here suggest that LF adaptations evolved in parallel in both the mysticete and proboscid lines over similar time scales and despite media differences. However, the results reported in this study should be viewed as preliminary because they are hampered by small sample size and preservation artifacts inherent in any study dependent on postmortem material from stranded animals. It is worthwhile noting that the scanning techniques used in this study are equally applicable to fossil material, and preliminary studies in this laboratory on a limited set of paleontologic specimens of gomphothere, mastodon, mammoth, and archaeocete ears show promising results for addressing evolutionary trends in these groups. To properly address these questions, both more fossil and rare extant material should be examined with nondestructive CT techniques.

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Chapter 65
What We Can Learn from Artificial Lateral Line Sensor Arrays

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Abstract The lateral line system of fish is important for many behaviors, including spatial orientation, prey detection, intraspecific communication, and entraining. With aid of the lateral line, fish perceive minute water motions. The smallest sensory unit of the lateral line is the neuromast, which occurs freestanding on the skin and in fluid-filled canals. We have built artificial lateral line canal systems that can be used to measure spatiotemporal flow patterns. Those patterns can, for instance, be used to distinguish between different environments and upstream objects.

Keywords Sensor • Biomimetic • Lateral line • Mechanosensory • Object discrimination

1 Introduction

Fish sense weak water motions and pressure gradients with their mechanosensory lateral line. Therefore, it is not surprising that the lateral line is one sensory system that provides information for spatial orientation, prey detection, predator avoidance, schooling, intraspecific communication (for a review, see Bleckmann 1994), and station holding (Liao 2007; Przybilla et al. 2010). The smallest functional unit of the lateral line is the neuromast, a sensory structure that occurs freestanding on the skin and in fluid-filled canals. Neuromasts consist of a hair cell epithelium and a gelatinous cupula (Flock and Wersäll 1962). The lateral line system of fish shows a high morphological diversity. Fish may have many (*Carassius auratus*) or only a few (*Barbatula barbatula*) superficial neuromasts (e.g., Schmitz et al. 2008; Beckmann et al. 2010). Lateral line canals may be simple, tapered, or branched.

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Additionally, some fish have no (e.g., *Brachydanio rerio*), one, or even multiple trunk canals on each body side (Coombs et al. 1988; Webb 1989; Bleckmann and Münz 1990). Fish may be exposed to different types of hydrodynamic signals and noise depending on their habitat (e.g., limnic vs. rheophilic species, open ocean vs. intertidal species) and behavior. Therefore, it is not surprising that the lateral line system is highly diverse. The response properties of primary lateral line afferents depend on various morphological parameters of the system. For instance, the diameter of the lateral line canal, neuromast size, and the stiffness of neuromasts alter the frequency response of a lateral line system (Denton and Gray 1988; van Netten 2006; McHenry et al. 2008) and trunk lateral line canals shield canal neuromasts from DC flow (Engelmann et al. 2000, 2002). In addition, the spatial distribution of canal pores influences the signal-to-noise ratio (Klein et al. 2013).

In the present study, we have built artificial lateral line canals (ALLCs) that were equipped with artificial neuromasts (ANs; Klein 2009; Klein and Bleckmann 2011; Klein et al. 2013). The main objective of our study was to uncover how upstream objects influence the stimuli received by ANs and whether it is possible to discriminate between different objects and hydrodynamic environments.

2 Materials and Methods

This work focuses on how lateral line information might be used to discriminate between different objects exposed to (1) flow and (2) different flow environments. For measurements, optical ANs (Klein and Bleckmann 2011; Klein et al. 2013) were used. In short, light was guided through a silicone bar situated inside a fluid-filled canal. The lumen of the canal was connected to the outer fluid via canal pores. Pressure differences at neighboring pores caused water motion inside the canal that, in turn, deflected the silicone bar. The position of the light spot leaving the tip of the silicone bar was measured with a position-sensitive device.

2.1 Discrimination of Upstream Objects

An array of four ANs (pore distance 6.5 mm, pore diameter 2.5 mm, distance between sensors 15 mm) was inserted inside the wall of the experimental section (11 cm wide, 36 cm long, 11 cm high) of a flow channel. During experiments, four flow velocities (0.0, 6.9, 10.3, and 12.4 cm/s) were applied. Objects with semicircular and rectangular cross sections were build (1 cm × 0.5 cm, 2 cm × 1 cm, and 3 cm × 1.5 cm; see Fig. 65.1). An experimental iteration consisted of a set of all permutations of flow velocities and objects in random order. Objects were placed 3 cm upstream of the most upstream AN of the sensor array. The distance between the wall and the objects was 1 cm (1-cm-wide objects), 1.5 cm (2-cm objects), and

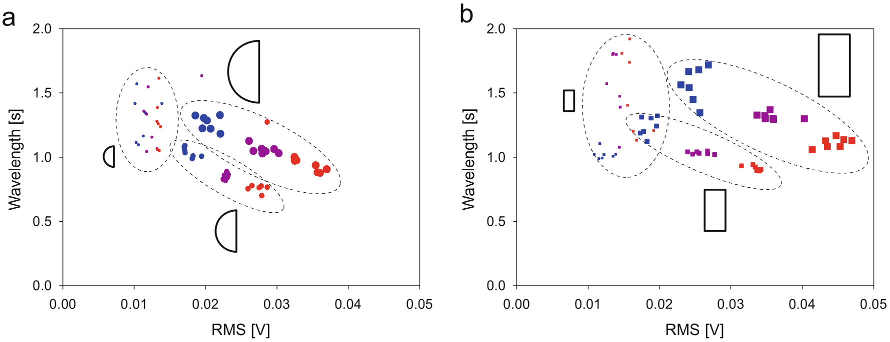

Fig. 65.1 Signal main wavelength as a function of root-mean-square (rms) of artificial neuromast signal. The sensor array was exposed to upstream objects with semicircular (**a**) and rectangular (**b**) shapes in cross section. Objects had different sizes (1-, 2-, and 3-cm marker size) and flow velocity was altered (*blue*, 6.9 cm/s; *violet*, 10.3 cm/s; *red*, 12.4 cm/s). Most points with equal experimental conditions clustered together. Therefore, it was possible to discriminate object size. Objects of 1 cm produced weak signals that were not detectable by the artificial neuromast array. As expected, rms increased and wavelength decreased with increasing flow velocity

2 cm (3-cm objects). Additionally, the sensors were exposed to flow without any objects being present. Seven experimental iterations were conducted. Sensor signals were measured for a period of 60 s (sampling rate 1 kHz). To reduce the amount of data, the wavelength (1/peak frequency), magnitude of peak frequency, maximal slope of the waveform, and the root-mean-square (rms) of the signal were extracted. Note that only wavelength and rms values are discussed in this paper.

2.2 Discrimination of Flow Environments

A fishlike sensor platform (3.6 cm wide, 20 cm long) was built and equipped with four ANs on each side. Interpore distance was 7 mm. Experiments were conducted inside the experimental volume (28.5 cm × 30 cm × 100 cm) of a flow channel. A 0.46-m-long part of the experimental section was symmetrically divided in flow direction by a plate. The flow on one side of the plate was disturbed by 4 half cylinders (5 cm wide), whereas the flow on the other side was unhindered. Half cylinders were attached with their flat side to the plate and the wall of the flow tank, respectively. The distance in stream direction between the two half cylinders on the wall and the two half cylinders on the plate was 34 cm. Five flow velocities (0.15, 0.19, 0.23, 0.3, and 0.35 m/s) were applied. The sensor platform was placed 5 cm downstream of the downstream end of the plate. The position of the sensor platform was altered in 1-cm steps perpendicular to flow direction. Stimuli were sampled for 60 s (1 kHz). The rms of the stimuli was calculated and evaluated as function of platform position.

3 Results

3.1 *Discrimination of Upstream Objects*

Signal wavelength and rms values differed among different experimental conditions (Fig. 65.1). Data of equal experimental conditions clustered for all permutations of object and flow velocity. Small objects and a low flow velocity led to lower rms values than bigger objects and higher flow velocities (Fig. 65.1). The wavelength for the 2- and 3-cm objects decreased with increasing flow velocity (Fig. 65.1, blue: low flow velocity, red: high flow velocity).

3.2 *Discrimination Between Different Flow Environments*

The flow tank was divided into two regions. The fluctuation of AN signals (rms values) was higher inside the turbulent region than inside the laminar region (Fig. 65.2a–f). ANs of the array that were located on the side which faced the turbulent region (Fig. 65.2b, d, f) received the turbulences earlier, indicated by an earlier increase in rms values, than ANs that were located on the other side (Fig. 65.2a, c, e). Signal delay that was calculated from the cross-correlation of AN signal decreased with increasing flow velocity (Fig. 65.2g). More data points with a correlation coefficient bigger than 0.4 were retrieved if the ANs faced the turbulent region (Fig. 65.2g).

4 Discussion

Our data show that an artificial lateral line can be used to discriminate between different upstream objects even if the flow velocity is altered. In addition, an artificial lateral line can be used to discriminate between turbulent and nonturbulent environments.

In case of the flow-exposed half cylinders, the peak frequency measured with artificial lateral lines increases with increasing flow velocity and decreasing half cylinder diameter (Klein and Bleckmann 2011). This is in line with the theoretical vortex-shedding frequency (f) in a wide range of Reynolds numbers (Vogel 1994): $f=0.2*v/d$, where v is flow velocity and d is cylinder diameter d. Therefore, the parameter peak frequency is not sufficient to discriminate object size if the flow velocity is not known. However, artificial lateral lines can also be used to measure bulk flow velocity by using time-shifted patterns along an array of ANs (Klein and Bleckmann 2011). Here we show that for objects positioned upstream but close to the sensory array, the signal rms values can also be used for the discrimination of object size.

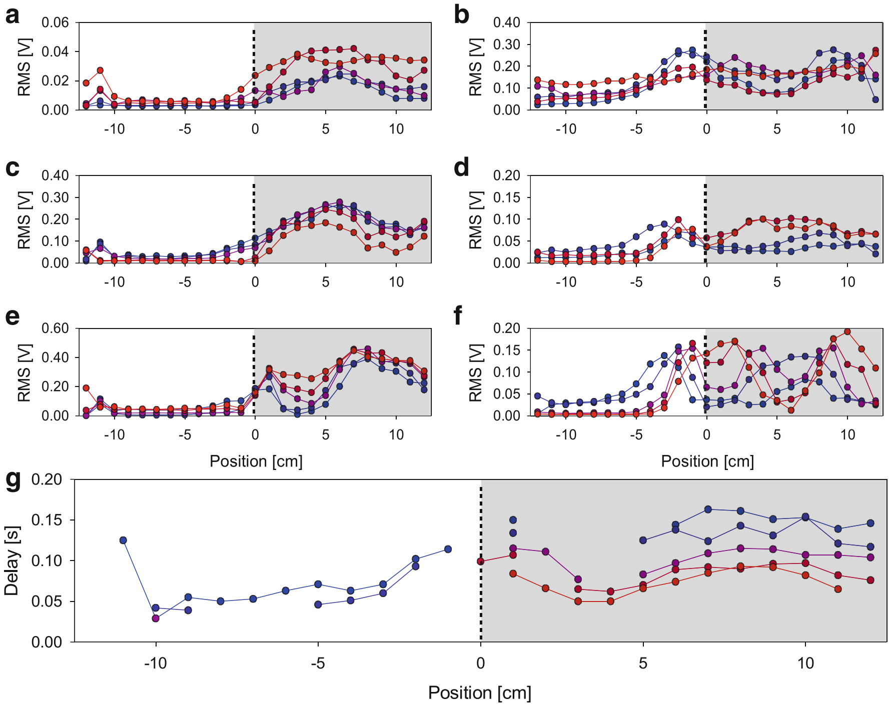

Fig. 65.2 Signal output rms (**a**–**f**) and signal delay of two artificial neuromasts (ANs) from the left array side (**g**) as function of sensor array position inside the flow tank. The flow tank was divided by a plate into two regions. In one region (−12 to 0 cm), flow was unhindered, whereas in the other region (0 to 12 cm), flow was disturbed by objects. The sensor array had two sides. The first (**a**), third (**c**), and fourth (**e**) ANs of the array received the turbulences later than the first (**b**), second (**d**), and third (**f**) ANs of the array. The array could be used to distinguish between a turbulent (*shaded*) and a nonturbulent (*nonshaded*) environment by using the rms. The signal delay between the third (**c**) and fourth (**e**) ANs decreased with increasing flow velocity (*blue*, low-flow velocity; *red*, high-flow velocity). Only data points with a high correlation (>0.4) are shown in (**g**)

Water movements in natural streams may be more complex than the water movements behind stationary objects exposed to laminar flow. To account for this, we exposed many objects simultaneously to flow and compared the flow regimen behind these objects with laminar flow. As expected, signals of the lateral line array differed in rms values between the two experimental conditions. Additionally, we could confirm (Klein and Bleckmann 2011) that signal delay between adjacent ANs decreased with increasing flow velocity. Interestingly, the peak cross-correlation values obtained from measurements inside the turbulent region often reached higher (>0.4) correlation values than the cross-correlation values obtained from measurements inside the laminar region. This indicates that turbulences are advantageous for estimating bulk flow velocity with the cross-correlation technique (Chagnaud et al. 2007; Klein and Bleckmann 2011).

Blind cave fish can image their surroundings with their lateral line (*Anoptichthys jordani*; Hassan 1989), and surface-feeding fish can localize and discriminate objects on the water surface (Bleckmann 1988). Our knowledge of algorithms used by fish for the processing of mechanosensory lateral line input for the discrimination of upstream objects and running water habitats is in its infancy and clearly needs many more measurements.

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Chapter 66
Protection of Marine Mammals

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Abstract Within the European Defense Agency (EDA), the Protection of Marine Mammals (PoMM) project, a comprehensive common marine mammal database essential for risk mitigation tools, was established. The database, built on an extensive dataset collection with the focus on areas of operational interest for European navies, consists of annual and seasonal distribution and density maps, random and systematic sightings, an encyclopedia providing knowledge on the characteristics of 126 marine mammal species, data on marine mammal protection areas, and audio information including numerous examples of various vocalizations. Special investigations on marine mammal acoustics were carried out to improve the detection and classification capabilities.

Keywords Marine mammal database • Risk mitigation • Classification

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1 Introduction

Exposure to active sonar can affect marine mammals negatively, especially beaked whales stranded on several occasions in the vicinity of antisubmarine warfare exercises where active sonar was used (e.g., Frantzis 1988; Simmonds and Lopez-Jurado 1991). These events caused concerns at various levels such as naval, public, governmental, and nongovernmental organizations. Active sonar sensors are essential for the navies. They must find the right balance between environmental concerns and operational issues. If the navies fail to establish risk mitigation measures, this could result in unnecessary restrictions during active sonar training.

In the last several years, various military organizations all over the world have established marine mammal risk mitigation teams to coordinate and carry out the necessary research because exact correlations between the strandings and sonar

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use are still unknown. Those teams also support the navies by establishing risk mitigation guidelines based on the latest research results and by helping them to plan sonar exercises. Therefore, the knowledge of marine mammal distribution in possible sonar exercise areas is essential. This knowledge is based on surveys, random sightings, and strandings as well as on habitat models.

Early detection, localization, and classification of marine mammals in a sonar exercise area can help avert further harm to the animals. Therefore, worldwide, new passive acoustic monitoring technologies are being developed and tested. New classification algorithms are being developed to classify detected whales because some species like Cuvier's beaked whales (*Ziphius cavirostris*) are apparently more vulnerable to sonar than others (e.g., Southall et al. 2007; Zimmer and Tyack 2007; Tyack et al. 2011).

The EDA PoMM project is based on an agreement between the Ministries of Defense from Germany, Italy, The Netherlands, Norway, Sweden, and the United Kingdom. The 3-year project started in August 2010. It aims to protect marine mammals against the impact of active sonar while maintaining the ability to operate active sonar. The project mainly consists of two work packages. Within the first work package, a comprehensive common marine mammal database, essential for risk mitigation tools, was established. The second work package comprises special investigations on the characteristics of marine mammal acoustics to improve the detection and classification capabilities.

2 Work Package 1: Marine Mammal Database

For successful risk mitigation measures during sonar exercises, extensive knowledge of marine mammals in all areas of operational interest for European navies is necessary. The established common MySQL database is focused on seasonal and annual distribution and density maps of various species but also contains systematic and random sightings as well as strandings. Besides this information, the database also contains an encyclopedia that provides knowledge on the characteristics of 126 marine mammal species. This includes the appearance, behavior, swim and diving characteristics, acoustic vocalization, and maps of general abundance. A further part of the database contains numerous examples of various vocalizations of different species. This audio part was used in work package 2 to set up and test marine mammal classifiers. Information on marine mammal protection areas worldwide is also included in the database.

In the beginning of the project, the members agreed on the general content and structure of the database, which consists of various tables described in the final report on the project. To collect a considerable amount of data, other countries allowed to each participant to look in the databases for suitable datasets besides the national ones. A common letter with a request for data was designed and distributed to many institutions worldwide. Several datasets were obtained from the Ocean Biogeographic Information System-Spatial Ecological Analysis of Megavertebrate

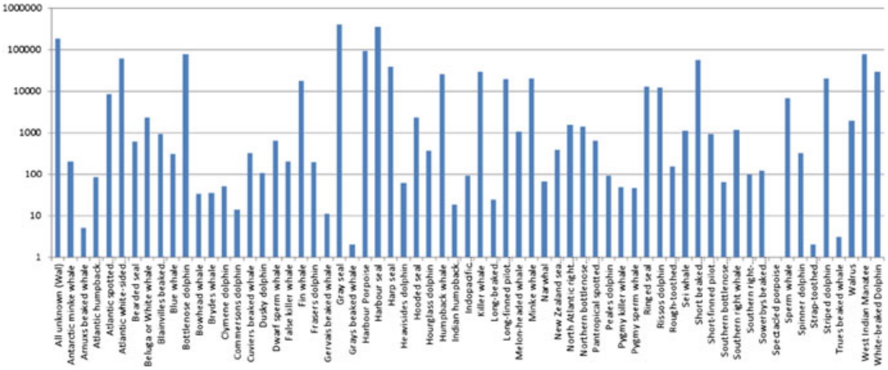

Fig. 66.1 Number of observations of unknown and 64 identified species collected until June 2013 and stored in the protection of marine mammals (PoMM) database

Populations (OBIS-SEAMAP), and data owners were asked for permission to use their data in the PoMM database. More than 1.5 million observations of unknown and 64 identified species were collected until June 2013 (Fig. 66.1). Most of the observations were made in the North Atlantic and adjacent seas. Data from various institutes are expected to arrive within the next months.

Annual and seasonal distribution and density maps that are available for many species are based mainly on the relative environmental suitability (RES) model (Kaschner et al. 2006). The model looks for suitable habitats for each species based on depth, sea surface temperature, and distance to the ice edge and land. As an example, the predicted seasonal density of Trues beaked whales (*Mesoplodon mirus*) is shown for summer and winter (Fig. 66.2). The density data are derived from additional military layer (AML) information.

Appropriate input tools were developed to insert encyclopedia, observation, distribution, and audio data into the database. Output tools were also generated that enabled extraction and visualization of the collected data. Furthermore, tools for validating the inserted data and checks for double entries were developed and were and will be applied whenever new datasets are entered into the database. The present location of the PoMM database is in an Italian server. At the end of the project in September 2013, the database will be distributed to all participating members because it is uncertain how long the Italian server will be maintained.

3 Work Package 2: Investigations on Marine Mammal Acoustics

One part of this work package was to develop tools and concepts for the acoustic detection of marine mammals. The detection ranges of simple hydrophones were estimated for four species: sperm whale (*Physeter macrocephalus*), Cuvier's beaked

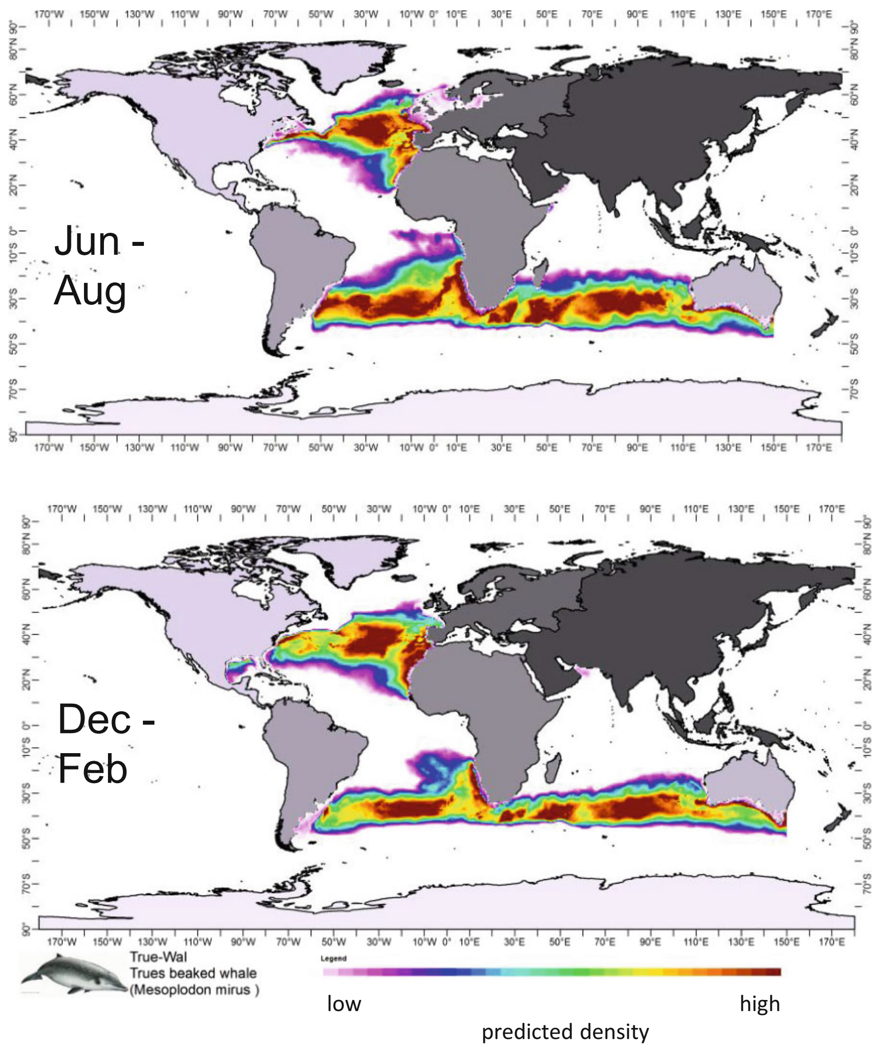

Fig. 66.2 Predicted density of True beaked whales during summer (June–August) and winter (December–February)

whale (*Ziphius cavirostris*), bottlenose dolphin (*Tursiops truncatus*), and harbor porpoise (*Phocoena phocoena*). They varied between 34 and 35 m. A conclusive document about existing passive acoustic monitoring (PAM) tools and their features is in preparation.

Another part of this work package was to provide a tool for the acoustic classification of marine mammals, considering particularly the critical groups and species mostly affected by active sonars. One classifier was developed by Germany within the project. It was tested and compared with a classifier called Delphinus intercept processor (DIP) developed previously by the Netherlands Organization for Applied Scientific Research (TNO). For training and testing the classifiers, acoustic events of different species were labeled and stored in the database. Therefore, a special tool for labeling and testing was developed. The stored acoustic events were divided into separate training and test sets. The detailed results of the classifier tests will be presented in the final report of the project, but it is already obvious that more labeled events are needed to improve the training of the classifier. The first classification results of the TNO classifier are shown in Table 66.1. Not all events from the test set were classified because the DIP has a built-in detector; only the events that produced a detection were classified.

4 Outlook

A follow-on EDA project, PoMM2, is planned by the current participating member states (pMS) to avoid negative impact on marine mammals by military active sonars. The precise aim of this project is to improve detection, classification, and localization (DCL) skills and to develop and validate common risk assessment methodology and evaluate mitigation procedures including an improvement of the common marine mammal database established during PoMM.

Performance in the DCL of marine mammals will be improved within PoMM2 for real-time processing using advanced algorithms, beam forming, ranging, and tracking.

Several nations have so far implemented very different procedures for marine mammal risk mitigation. The level of knowledge on how marine mammals are affected by sonar has increased significantly in the last years, and it should now be possible to converge on a common risk assessment methodology and provide the necessary information for mitigation procedures. The project will make a joint recommendation to all pMS on a methodology for determining the risk of impact of sonar systems and advise on the efficacy of different mitigation measures by using simulations and real-life observations. In the project methods, algorithms and modules for calculations (demonstrators) will be developed. These modules can be used by pMS as the building blocks for designing or improving existing operational planning tools.

The marine mammal database developed during the EDA PoMM project will be improved and extended with new data and parameters. New methods for generating density maps will be developed. The database is an essential input for the common risk assessment procedure.

The outline description of PoMM2 was submitted to the EDA in June 2013 and was circulated among the member states to check for possible interest. Within the next several months, work packages and financial contributions as well as a project agreement (PA) will be drafted in detail and sent to the EDA for national staffing. We expect PoMM2 to start in 2015.

Table 66.1 Classification results of the Dutch classifier Delphinus intercept processor (DIP) for audio events of seven different species and groups of the test set

	Estimated labels							
True labels	1. Large Baleen Whale	2. Small Baleen Whale	3. Cuvier's Beaked Whale	4. Northern Bottlenose Whale	5. Dolphin	6. Porpoise	7. Seal	Total
1	8 (32%)	5 (20%)	0	0	9 (36%)	0	3 (12%)	*25*
2	4 (11%)	19 (53%)	0	0	8 (22%)	0	5 (14%)	*36*
3	0	0	124 (69%)	55 (31%)	0	0	0	*179*
4	0	0	26 (14%)	155 (85%)	0	0	2 (1%)	*183*
5	9 (8%)	0	17 (16%)	4 (4%)	77 (71%)	0	2 (2%)	*109*
6	0	0	0	0	0	67 (100%)	0	*67*
7	7 (15%)	5 (10%)	0	1 (2%)	8 (17%)	0	27 (56%)	*48*
Total	*28*	*29*	*167*	*215*	*102*	*67*	*39*	*647*

The last column shows the total number of events present for each species or group. All correct classifications are located on the diagonal of the table

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Chapter 67
Avoidance of Pile-Driving Noise by Hudson River Sturgeon During Construction of the New NY Bridge at Tappan Zee

Justin Krebs, Fred Jacobs, and Arthur N. Popper

Abstract Sturgeon movements were monitored during a pile-driving operation. Fewer sturgeon were detected during pile driving and remained for a shorter time than during silent control periods. Moreover, the short time spent by sturgeon near pile driving suggests that they were unlikely to have reached the criterion of 187 dB re 1 μPa^2·s cumulative sound exposure level. These results suggest that sturgeon are likely to avoid impact pile driving and not remain long enough to experience physiological effects, thus providing empirical evidence that the 206 dB re 1 μPa peak sound pressure level is the appropriate criterion for assessing the impacts of pile-driving noise on sturgeon.

Keywords Hydroacoustics • Barotrauma • *Acipenser* • Acoustic tag • Isopleth

1 Introduction

There have been very few studies that have examined behavioral effects, including avoidance behavior, of pile driving on fish. In most earlier studies, as reviewed by Popper and Hastings (2009), fish were held in small cages where behavior is severely constrained and so would not be representative of a natural setting. For the results of an empirical study to be relevant to an assessment of the potential for pile driving or other anthropogenic stimuli to affect fish and other aquatic biota, such a study must examine free-swimming wild animals.

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In connection with the construction of the New NY Bridge at Tappan Zee on the Hudson River in New York (see Chapter 106 by Popper et al. for a further discussion of the Tappan Zee Bridge replacement and Chapter 60 by Jacobs et al. for a discussion of the regulatory permitting process), a Pile Installation Demonstration Project (PIDP; Martin et al. 2012) was conducted to (1) assess the geotechnical aspects of the construction site; (2) collect hydroacoustic-monitoring data on underwater noise levels generated by the PIDP pile-driving operations; (3) evaluate the effectiveness of several noise attenuation systems (NASs) for minimizing noise impacts on Hudson River fishes; and (4) monitor for the presence of acoustic-tagged fishes, including Atlantic sturgeon (*Acipenser oxyrhinchus*), and evaluate their behavioral response to the underwater noise associated with pile-driving activities. The present study focused specifically on the behavior of tagged sturgeon during pile driving to determine the likelihood that sturgeon would avoid pile-driving noise.

2 Methods

2.1 Sturgeon Monitoring During Pile Driving

Pile-driving events were conducted at four locations, PLT-1, PLT-2, PLT-3, and PLT-4, along the path of the planned bridge (Fig. 67.1). An "event" consisted of driving one or two piles at a location over several hours on a single day. Acoustic-tagged Atlantic sturgeon were monitored in the vicinity of pile-driving activities from 23 April to 20 May 2012 using four VEMCO VR2W acoustic-monitoring receivers that were deployed across the river at Stations 4, 5, 6, and 7 and approximately in-line with the pile-driving locations (the receiver at Station 5 was not recovered). Data identifying the individual Atlantic sturgeon and the time and date in which its transmitter was detected by the acoustic receiver (i.e., when the sturgeon was present in the receiver "detection area") were recorded for each detection.

2.2 Extent of the Sturgeon Detection Area

The total extent of the detection area for one receiver was ~78 hectares. Because only two tagged Atlantic sturgeon were detected at Station 4, our analyses were conducted for the detection area monitored by Stations 6 and 7 only, which covered ~156 hectares. The extent and location of the areas ensonified at 150 dB re 1 μPa root-mean-square sound pressure level ($\mathrm{SPL_{rms}}$), 187 dB re 1 $\mu\mathrm{Pa}^2\cdot\mathrm{s}$ cumulative sound exposure level ($\mathrm{SEL_{cum}}$), and 206 dB re 1 μPa peak SPL ($\mathrm{SPL_{peak}}$) are shown relative to the detection areas in Fig. 67.1. The ensonified areas at 206 dB re 1 μPa $\mathrm{SPL_{peak}}$ and 187 dB re 1 $\mu\mathrm{Pa}^2\cdot\mathrm{s}$ $\mathrm{SEL_{cum}}$ for Stations 6 and 7 were considerably smaller than those in the detection area (<0.2 and <3%, respectively); therefore, a tagged

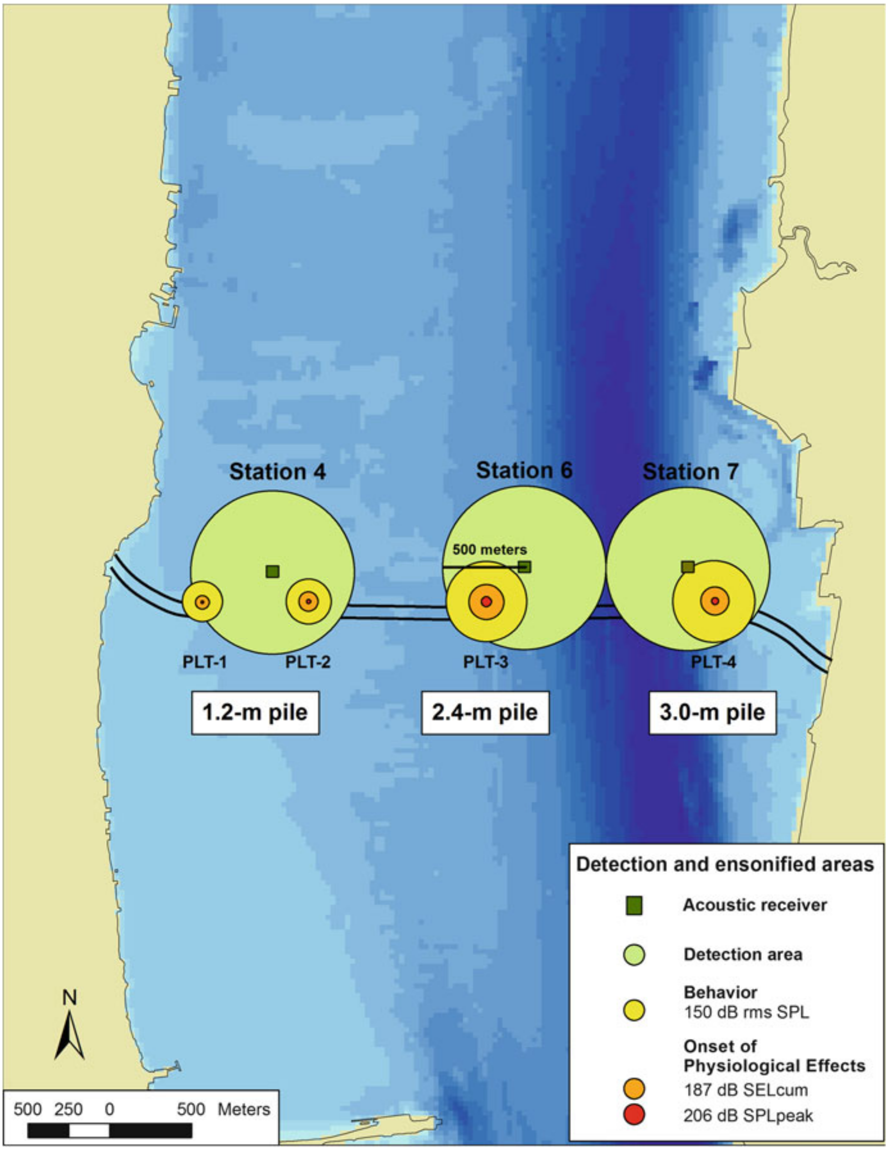

Fig. 67.1 Relative size and location of detection areas sampled by acoustic monitoring receivers during the Pile Installation Demonstration Project (PIDP) relative to the extent of the ensonified areas (based on noise measurements taken during the PIDP with noise attenuation system off). The detection radius of 500 m is indicated by the horizontal black line extending from the receiver at Station 6. *SPL* sound pressure level, *rms* root-mean-square, SEL_{cum} cumulative sound exposure level

sturgeon could be detected by the receiver in the vicinity of pile driving that was not necessarily in the ensonified area. Although it was not possible to know the specific location of tagged sturgeon within the detection area relative to the area that was ensonified at 187 dB re 1 μPa^2·s SEL$_{cum}$ (Fig. 67.1), the ensonified area was within the detection area. Therefore, it is reasonable to conclude that any fish that did not remain in the larger detection area for the duration of the pile driving were not in the smaller ensonified area for that period either.

2.3 Time Spent by Individual Atlantic Sturgeon Within the Detection Area

Sturgeon could potentially show the onset of physiological effects if enough time is spent in proximity of sufficiently loud pile-driving activities. To examine the likelihood that sturgeon would be exposed to sufficient cumulative noise to reach the 187 dB re 1 μPa^2·s SEL$_{cum}$ criterion for the onset of physiological effects, time spent by tagged sturgeon within range of the acoustic receiver was estimated as the sum of detection times recorded by the acoustic receiver. Total time for each sturgeon was calculated using the instantaneous observations of tagged sturgeon recorded by the acoustic-monitoring receivers at 1-min intervals. It was assumed that consecutive detections occurring <5 min apart indicated continuous time spent within the detection area. Consecutive detections occurring at intervals >5 min were each counted as separate events.

To account for missed detections caused by interference among concurrent tag transmissions from different animals (i.e., code collision) and to ensure that noise-exposure time was not underestimated, it was assumed that detected sturgeon remained in the range of the receiver for the maximum time period required to detect all individuals, assuming that code collision was occurring. For example, in the absence of code collision, each tagged sturgeon would have been detected every 2 min as long as it remained in the detection area. In the case of four co-occurring tagged sturgeon, it would take a maximum of 7 min to detect all four fish when accounting for missed detections caused by code collision. Therefore, if any of these fish were detected during a 10-min continuous pile-driving event but not detected again during that period of time, it was assumed that those fish had remained in the detection area for 7 min of pile driving before leaving the detection area (whether or not the fish actually remained in the detection area for the full 7 min). Because of the frequency with which each tag transmits, sturgeon could not have remained longer without being detected, even in the event of code collision. This approach to estimating "time spent" is highly conservative and likely overestimated the actual time spent by sturgeon in the detection area.

The maximum time required to detect all tagged Atlantic sturgeon was based on the times reported for the A69-1601 series tags in the VEMCO manual (http://www.vemco.com/products/transmitters/index_coded.php) and were increased by 30% as recommended by VEMCO to account for possible differences in tag transmission characteristics between the A69-1601 series tags and the A69-9001 series tags that were used to tag the sturgeon. Detection data were reviewed by Dr. Dale Webber at VEMCO who determined that the likelihood of code collision was minimal for this particular dataset (i.e., >90% of tag transmissions were received).

2.4 Avoidance Analysis

Time spent by individual sturgeon within the detection area was used to determine whether or not tagged Atlantic sturgeon avoided the detection area during active pile driving during the PIDP compared with time spent during the same length of time just before the "work window." The work window was defined as the period of time starting when the crews arrived on the barges and ending when the crews left the barges. Active pile driving was among the activities that occurred during the work window. This comparison was made using the Wilcoxon signed-rank test (a standard nonparametric statistical test that compares paired observations of "time spent" for individual sturgeon). It was hypothesized that detection time would be significantly less during active pile driving compared with the time period just before the work window if tagged Atlantic sturgeon had avoided pile driving. Hammer type (impact vs. vibratory) and proximity to pile driving (near vs. distant) were included as factors in the comparisons. The null hypothesis of no difference in detection time was tested for the before work window versus during time periods for both hammer types and for near and distant piles using the nonparametric Wilcoxon signed-rank test on paired observations. Paired data consisted of observations of time spent by individual tagged sturgeon that were detected before the work window and during active pile driving. A Bonferroni correction was used to account for multiple hypothesis tests ($n = 2$ hammer types × 2 distances = 4 tests) and to ensure that spurious results were not accepted as significant. It was expected that pile-driving events conducted using impact hammers would result in greater avoidance by tagged Atlantic sturgeon because of the higher sound pressures produced by the impact hammer compared with the vibratory hammer. Similarly, it was expected that large piles driven within the detection area for receiver Stations 6 and 7 (PLT-3 and PLT-4) would cause greater avoidance than small piles driven at distant locations outside the detection area (PLT-1 and PLT-2).

2.5 Likelihood of Reaching the Threshold for the Onset of Physiological Effects

After accounting for the potential undetected time caused by code collision, the time spent in the detection area by each tagged sturgeon was used to estimate the probability that tagged sturgeon would exceed the 187 dB re 1 $\mu Pa^2 \cdot s$ SEL_{cum} criterion for the onset of physiological effects. The purpose of the analysis was to answer the question: "What is the probability that sturgeon will remain close enough to pile-driving activities to reach the cumulative level of noise exposure necessary to cause onset of physiological effects?"

This probability was represented as the percentage of the detection area encompassed by the 187 dB re 1 $\mu Pa^2 \cdot s$ SEL_{cum} ensonified area. We assumed that sturgeon were randomly distributed throughout the detection area and were not avoiding or attracted to pile-driving activities. If sturgeon avoided pile-driving activities, the likelihood of the onset of physiological effects would have been even less than the estimates derived through this analysis. As an example, if the extent of the ensonified area encompassed the entire detection area (i.e., 100%), all of the sturgeon detected during the PIDP would have reached the onset threshold for physiological effects if they were exposed for the full time required to drive the pile. Smaller ensonified areas encompass less of the detection area and so the probability that sturgeon would reach the threshold for the onset of physiological effects would be reduced. Thus, if the ensonified area is 50% of the detection area, the likelihood of reaching the onset threshold would be 50%. Similarly, if pile-driving noise was not loud enough to reach the cumulative exposure level that would result in the onset of physiological effects, the ensonified area would be 0% of the detection area and there would be no chance that sturgeon would reach the threshold. Because the amount of cumulative sound to which fish are exposed increases with the amount of time spent in the vicinity of pile driving, the probability of reaching the onset threshold for physiological effects would be further reduced if sturgeon spent less time in the detection area. For each strike of the pile, the ensonified area increases in size as does the probability that a detected sturgeon will occupy that area.

For each sturgeon detected during impact pile driving for 1.2-m-, 2.4-m-, and 3.0-m-diameter piles during the PIDP, the number of minutes spent in the detection area during active pile driving (after adjusting for the effects of code collision) was converted to the number of pile strikes that the sturgeon would have experienced over that time. This was done using the strike rate per minute from the PIDP. The number of pile strikes was then used to estimate the area surrounding the pile that each sturgeon would need to occupy to reach the 187 dB re 1 $\mu Pa^2 \cdot s$ SEL_{cum} criterion. This ensonified area was expressed as a percentage of the detection area to estimate the probability of reaching the criterion.

3 Results

3.1 Detection of Acoustic-Tagged Sturgeon

Over the course of the 4-weeks PIDP, 155 uniquely tagged sturgeon were detected, producing a total of 32,603 individual detections. Of these, 82 sturgeon were found in the detection area during the pile-driving work windows, which included non-pile-driving activities. During the work window for vibratory pile driving (1.2-m piles at PLT-1, PLT-2, and PLT-3; 3.0-m pile at PLT-4), only two of the 31 sturgeon observed were present during active pile driving (for up to 21 min), and neither of those fish remained in the detection area for the duration of the pile driving event (i.e., 115 min) even after accounting for code collision. Given the relatively large size of the detection area compared with the area in which sturgeon are likely to reach the cumulative criterion of 187 dB re 1 $\mu Pa^2 \cdot s$ SEL_{cum}, it is unlikely that these sturgeon would have reached that threshold.

During the work window for impact pile driving of small piles (1.2 m) at PLT-1, PLT-2, and PLT-3, 28 sturgeon were detected, but only 5 of those sturgeon were detected during active pile driving. The same was true during the work window for the large piles (2.4 m and 3.0 m) driven with the impact hammer at PLT-3 and PLT-4; in this case, 23 sturgeon were detected, but only 1 of those sturgeon was detected during active pile driving. Most of the time spent in the detection area by these sturgeon occurred either before, after, or between active pile driving.

3.2 Probability of Sturgeon Reaching the 187 dB re 1 μPa²·s SEL$_{cum}$ Criterion for the Onset of Physiological Effects

Based on the time spent by sturgeon within the detection area during pile driving, sturgeon would have to have been within 16–58 m of the pile (depending on pile size) for the entire time that they were detected to reach the 187 dB re 1 μPa^2·s SEL$_{cum}$ threshold (Table 67.1). The probability that sturgeon were within this range for the entire detection time was <0.6% for all but one sturgeon; the probability for this fish was still extremely low at 1.3% (Table 67.1). These results indicate that there is a very low probability that sturgeon will spend enough time in proximity to pile driving (even after accounting for the effects of code collision) to reach the 187 dB re 1 μPa^2·s SEL$_{cum}$ threshold for the onset of physiological effects under the current interim West Coast noise criterion.

3.3 Sturgeon Avoidance of Pile-Driving Noise

Results of the Wilcoxon test demonstrated that the amount of time spent by Atlantic sturgeon in the detection area before pile driving with the impact hammer was significantly greater than the amount of time spent in the detection area during

Table 67.1 Time spent by tagged Atlantic sturgeon in the tag-detection area during impact pile driving and the probability that sturgeon reached the threshold of 187 dB re 1 μPa^2·s SEL$_{cum}$

Pile-driving event, m	Active pile-driving time, min	Number of fish detected during pile-driving window	Time spent by fish in tag-detection area during active pile driving, min	Distance from Pile to 187 dB SEL$_{cum}$, m	Probability of fish reaching 187 dB SEL$_{cum}$, %
1.2	50	7	0–15	16–20	0.1–0.2
2.4	73	5	6–38	24–58	0.2–1.3
3	30	17	4–29	18–37	0.1–0.6

Estimates of time spent accounted for the possibility of code collision. Probabilities are based on the size of the 187 dB re 1 μPa^2·s cumulative sound exposure level (SEL$_{cum}$) ensonified area relative to the size of the tag-detection area

Table 67.2 Time spent by tagged Atlantic sturgeon before and during pile-driving events

	Location of pile-driving event			
	Outside the detection area (PLT-1 and PLT-2)		Inside the detection area (PLT-3 and PLT-4)	
Hammer type	Impact	Vibratory	Impact	Vibratory
Number of sturgeon detected	17	22	48	25
Mean difference of time within detection area (before vs. during pile driving)	−5 min	8 min	11 min	<1 min
Wilcoxon *S*	−27.5	18	226	8
P	0.09	0.22	0.0024[a]	0.79

Results are from Wilcoxon signed-rank tests comparing time spent by tagged Atlantic sturgeon within the detection area during pile-driving events conducted as part of the Pile Installation Demonstration Project relative to time spent before construction activities

[a] Significant difference, indicating that fish spent an average of 11 min more in the detection area before the work window compared with the time period during active pile driving with the impact hammer

impact pile driving. When pile driving occurred at locations inside the detection area, tagged sturgeon spent significantly less time in the detection area during active impact pile driving compared with the time period just before the work window (Wilcoxon test, $P=0.0024$; Table 67.2). However, there was no difference in the amount of time spent in the detection area before versus during vibratory pile driving ($P=0.79$). When pile driving occurred at locations outside the detection area, there was no difference in the amount of time spent in the detection area before versus during active pile driving with the impact hammer ($P=0.09$) or with the vibratory hammer ($P=0.22$; Table 67.2). This finding was not unexpected because sturgeon in the detection area for Stations 6 and 7 would likely be unaffected by pile driving of 1.2-m piles at distant locations (PLT-1 and PLT-2). The analysis suggests that tagged Atlantic sturgeon avoided the detection area during impact hammering within the detection area but not when pile driving was conducted using the vibratory hammer or when pile driving (impact and vibratory) occurred outside the detection area.

4 Conclusions

We conclude that Atlantic sturgeon in the Hudson River are likely to avoid underwater noise associated with impact pile driving and are not likely to remain in the vicinity long enough to experience noise levels that would result in the onset of physiological effects. These conclusions are based on our observations that time spent by tagged sturgeon in the vicinity of test piles during impact pile driving was significantly less than time spent before pile driving. We have also demonstrated that the likelihood of Atlantic sturgeon reaching the 187 dB re 1 μPa^2·s SEL_{cum} even after accounting for the potential effects of tag interference (i.e., code collision) was extremely small during the PIDP (it only exceeded a probability of 1% for one fish). Sturgeon close enough to the pile to reach the threshold of 187 dB re 1 μPa^2·s SEL_{cum} within just a few strikes would also be close enough to experience SPLs of 206 dB re 1 μPa or greater. Accordingly, we have provided empirical evidence that the SPL_{peak} criterion is the appropriate metric for assessing the potential impacts of pile-driving noise on sturgeon. These results and those of Krebs et al. (2012) have been incorporated by the National Marine Fisheries Service into recent Biological Opinions (National Marine Fisheries Service 2012), including the Opinion for the Tappan Zee Bridge Replacement Project (National Marine Fisheries Service 2013), as support for sturgeon avoidance and as a basis for using the SPL_{peak} criterion rather than the SEL_{cum} criterion and should be considered for use in future impact assessments.

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The work reported here was conducted for the New York State Thruway Authority and the opinions expressed are those of the authors and do not necessarily reflect views of the Authority.

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Chapter 68
Methods for Predicting Potential Impacts of Pile-Driving Noise on Endangered Sturgeon During Bridge Construction

Justin Krebs, Fred Jacobs, Robert Conway, Arthur N. Popper, Mark Moese, John Rollino, Roberto Racca, Bruce Martin, and Alexander MacGillivray

Abstract The potential impacts of pile-driving noise on Hudson River sturgeon during construction of the New NY Bridge were predicted. Abundance data for shortnose and Atlantic sturgeon derived from fisheries sampling were combined with data about the spatial extent of pile-driving noise. This approach was used to calculate the number of sturgeon that could occur within sound level isopleths exceeding peak and cumulative noise criteria used by the National Marine Fisheries Service to determine the incidental take of sturgeon. The number of sturgeon subject to the potential onset of physiological effects during pile driving was predicted to be 35–41 fish for each species.

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1 Introduction

As part of the environmental permitting process for the New NY Bridge at Tappan Zee (see Chapters 106 by Popper et al. and 60 by Jacobs et al.), an assessment was undertaken to evaluate the potential impacts of pile-driving noise on Hudson River sturgeon. To do this, we estimated the spatial extent of underwater noise that may result from pile driving during bridge construction and then used these estimates to calculate the potential "incidental take" of endangered shortnose sturgeon (*Acipenser brevirostrum*) and Atlantic sturgeon (*Acipenser oxyrhinchus*) associated with the project. Incidental take (or "take") from pile driving is estimated as the potential number of shortnose and Atlantic sturgeon that may be exposed to underwater pile-driving noise that exceeds a predefined peak sound pressure level (206 dB re 1 µPa SPL_{peak}) or a cumulative sound exposure level (187 dB re 1 $µPa^2·s$ SEL_{cum}) that have been proposed as the thresholds for the onset of physiological effects for fishes (Stadler and Woodbury 2009) and used by the National Marine Fisheries Service (NMFS) to estimate take.

The NMFS determined, during its evaluation of the potential impacts to sturgeon, that it was unreasonable to assume that a sturgeon would remain close enough to pile-driving activities to reach the cumulative threshold for the onset of physiological effects (NMFS 2013). Therefore, the peak criterion was used as the basis for estimating potential sturgeon take resulting from the project. NMFS in its Biological Opinion also elected to use the take estimate for shortnose sturgeon as a conservative means to set the take for Atlantic sturgeon on the basis that there are fewer Atlantic sturgeon than shortnose sturgeon in the Hudson River (NMFS 2013). The purpose of this paper is to describe the various analytical approaches used to estimate the potential sturgeon take for this project.

2 Estimation of the Spatial Extent of Pile-Driving Noise Isopleths

Bridge construction will involve the driving of 1.2-m- (4-ft-) diameter piles (driven in water depths of <6 m) and 1.8-m- (6-ft-) diameter piles (driven in water depths of 6–12 m). Estimates of the ensonified areas associated with the 1.2-m piles were derived directly from SPL_{peak} data measured during a Pile Installation Demonstration Project (PIDP) conducted in May 2012. Because 1.8-m piles were not driven during the PIDP and because piles were not driven at water depths >6 m, PIDP noise data could not be used directly. Therefore, noise data collected during driving of a 2.4-m PIDP pile were used to approximate the distance to the 206 dB re 1 µPa SPL_{peak} for 1.8-m piles and then validated using the results of several California Department of Transportation (Caltrans) construction projects.

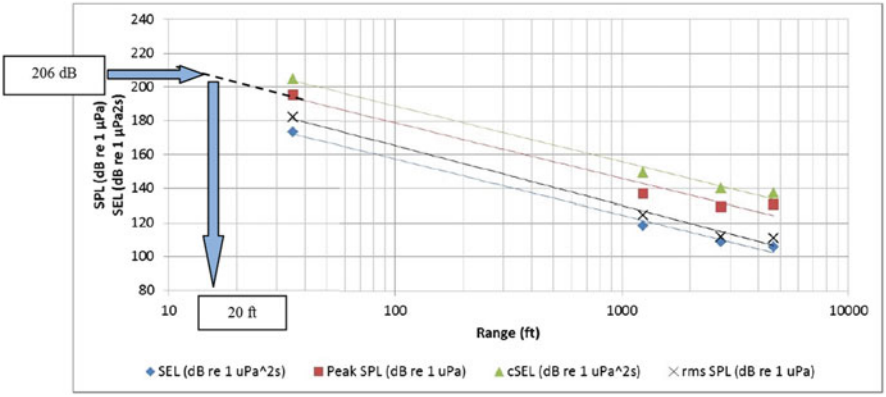

Fig. 68.1 Relationship between sound and distance from a 1.2-m pile driven during the Pile Installation Demonstration Project (taken from Martin et al. 2012). The sound data were used to determine the distance from the pile to the 206 dB re 1 µPa peak sound pressure level (SPL), which in this case was <6 m (see text). The other sound metrics plotted were not used in this discussion. The *blue arrows*, *dashed regression line*, and several data labels were added for the purpose of illustrating how the regressions were used to estimate isopleth size for AKRF's estimation of take. *SEL* sound exposure level

2.1 Piles 1.2 m (4 ft) in Diameter

The maximum distance from the pile at which the 206 dB re 1 µPa SPL_{peak} was reported during the PIDP was used to calculate the size of the ensonified area for 1.2-m piles with a noise attenuation system (NAS) in place (bubble curtains provided a reduction of 12–16 dB in SPL_{peak} for 1.2-m piles). An example of the regression relationship between SPL_{peak} and distance from a 1.2-m pile, as calculated from SPL_{peak} levels measured during the PIDP, is presented in Fig. 68.1. In Fig. 68.1, regression lines are drawn through the measured sound levels (*y*-axis) at various distances from the pile (*x*-axis, logarithmic). When the computed best-fit regression line for SPL_{peak} (red line) is extrapolated back toward the pile, it intersects 206 dB re 1 µPa on the *y*-axis at a distance of ~6 m from the pile. A radius of 6 m was therefore used to calculate the area ensonified at 206 dB re 1 µPa SPL_{peak} when estimating potential sturgeon take for pile driving of 1.2-m piles.

2.2 Piles 1.8 m (6 ft) in Diameter

Because 1.8-m piles were not driven as part of the PIDP, the distance to the 206 dB re 1 µPa SPL_{peak} isopleth for the 1.8-m piles was based on the distance observed during the PIDP for a 2.4-m pile driven with and without NAS noise reduction in 5 m of water. The use of the 2.4-m PIDP pile as a proxy for the 1.8-m piles was done with the understanding that the noise isopleth for the 2.4-m pile will be larger than that for the 1.8-m piles, which resulted in a conservative estimate of the distance to the SPL_{peak} and, ultimately, a conservative estimate of take. The measured distance from the 2.4-m pile to the 206 dB re 1 µPa SPL_{peak} isopleth (without NAS noise reduction) was 26 m. When we applied the 17-dB noise reduction (measured for the 2.4-m pile during the PIDP) to estimate attenuated distance (Martin et al. 2012, p. 41), the average distance to the 206 dB re 1 µPa SPL_{peak} isopleth was reduced to 10 m. Therefore, we assumed the approximate distance to the 206 dB re 1 µPa SPL_{peak} isopleth would fall somewhere between 10 and 26 m. The 2.4-m pile is not a perfect proxy because it was driven in shallow water (5 m), whereas the 1.8-m piles will be driven in deeper water (12 m) during bridge construction and the sound is expected to propagate further in deeper water. Nevertheless, the distance to the 206 dB re 1 µPa SPL_{peak} isopleth for the 1.8-m piles would be on the order of tens of meters rather than hundreds of meters and is likely to be <26 m as indicated by the 2.4-m PIDP pile driven without noise reduction. Therefore, to provide added conservatism, we estimated the distance to the 206 dB re 1 µPa SPL_{peak} to be ~15–30 m (rather than the earlier estimate of 10–26 m) given the data reported here and by Martin et al. (2012).

As a means of validating the predicted distance to the 206 dB re 1 µPa SPL_{peak} isopleth, the estimate of 15–30 m for a 1.8-m pile was compared with empirical data collected for a 2.4-m pile driven in 12 m of water during a Caltrans construction project (Benicia-Martinez Bridge) in the San Francisco Bay estuary (Caltrans 2009). Without noise reduction, the distance to the 206 dB re 1 µPa SPL_{peak} isopleth was measured 63 m from the pile. Assuming a 10-dB noise reduction, the distance to the 206 dB re 1 µPa SPL_{peak} was approximated to be 18.6 m based on SPL_{peak} data reported by Caltrans (2009). Because sound levels from a 1.8-m pile are generally less intense than for a 2.4-m pile, it follows that the distance to the 206 dB re 1 µPa SPL_{peak} isopleth for the 2.4-m pile in the same depth of water is an overestimate of the distance for the 1.8-m pile. Thus, if the distance in 12 m of water for a 2.4-m pile with noise reduction is 19 m, the distance for a 1.8-m pile in the same depth will be less. Therefore, a radius of 15–30 m was used to calculate the extent of the area ensonified at 206 dB re 1 µPa SPL_{peak} when estimating potential sturgeon take during pile driving of 1.8-m piles. To provide an estimate of sensitivity for potential sturgeon take, we calculated take assuming a radius of 15 m as well as a radius of 30 m, which allowed us to determine if a doubling of take would result from a doubling in the distance to the 206 dB re 1 µPa SPL_{peak} isopleth.

3 Estimation of Sturgeon Abundance to Calculate Take

3.1 Shortnose Sturgeon

Using fish abundance estimates from a 1-year comprehensive gill net sampling study, the encounter rate of shortnose sturgeon in the study area was estimated as the number of shortnose sturgeon collected per gill net per hour. From June 2007 to

May 2008, 476 gill nets were deployed just upstream of the existing Tappan Zee Bridge, for a total sampling time of 679 h. Sampling was conducted approximately every other month from April 2007 to May 2008. Based on the observed number of sturgeon collected and the given level of sampling effort, the encounter rate for shortnose sturgeon in the bridge construction area was calculated as 0.033 sturgeon/net/h of sampling.

To estimate the number of shortnose sturgeon that would potentially reach the onset of physiological effects as a result of pile-driving noise, it was necessary to scale gill net encounter rates from a single gill net sample (the gill net is 38.1 m in length) to the diameter of the ensonified area for the 206 dB re 1 μPa $\mathrm{SPL}_{\mathrm{peak}}$ isopleth. The number of shortnose sturgeon was estimated as the number that would have been collected if multiple gill nets were deployed side by side across the area ensonified by the $\mathrm{SPL}_{\mathrm{peak}}$ of 206 dB re 1 μPa. For example, if the diameter of the 206-dB $\mathrm{SPL}_{\mathrm{peak}}$ isopleth created during 1 h of pile driving for a 1.8-m pile was 60 m, then ~2 gill nets would be required to span the isopleth. In each of these gill nets, 0.033 shortnose sturgeon would be collected for each hour of pile driving based on the encounter rate described above. Therefore, the estimated take expected during pile driving for this single 1.8-m pile would be 0.05 sturgeon, calculated as

0.033 sturgeon/net/h × (60 m/38.1 m/gill net) × 1 h = 0.05 sturgeon.

This estimate was then summed with those for the other piles driven during a specific time period and rounded up to the nearest whole number. The sum of these partial takes over the entire time period required for pile driving during bridge construction equals the potential take for shortnose sturgeon.

3.2 Atlantic Sturgeon

Juveniles

Abundance of juvenile Atlantic sturgeon (<1,000-mm total length) was calculated using "sample volume-corrected" abundances from a long-term fishery sampling program conducted between 1998 and 2007 (i.e., Hudson River Utilities Fall Shoals Program). Data were stratified by sampling week, habitat (shoal, channel, bottom), and river segment (e.g., Tappan Zee, Hyde Park). Abundances were interpolated for weeks that were not sampled. The weekly average abundance was then calculated as the number of juvenile Atlantic sturgeon per cubic meter for each of the 52 calendar weeks. The estimated ranges from the pile to the 206 dB re 1 μPa $\mathrm{SPL}_{\mathrm{peak}}$ isopleth for the 1.2-m and 1.8-m piles were then used to estimate the area of these isopleths, which were combined with bathymetric data at each pile location to estimate ensonified water volumes. Potential take for juvenile Atlantic sturgeon over the course of bridge construction was estimated as a function of the ensonified volume during pile driving and the corresponding mean weekly sturgeon densities.

Subadults

The take for subadult Atlantic sturgeon was estimated using an approach similar to that used for shortnose sturgeon. However, instead of using the gill net encounter rate as a measure of sturgeon abundance, abundance was estimated using telemetry-monitoring data for acoustic-tagged Atlantic sturgeon detected by hydroacoustic receivers deployed near the Tappan Zee Bridge in April and May 2012. In total, 79 acoustic-tagged subadult sturgeon were detected during 636 h in an area of 236 hectares (the area sampled by three acoustic receivers). The abundance of tagged subadult sturgeon was compared with the total number of tagged Atlantic sturgeon in the population (assumed to be 198; K. Dunton, personal communication) and the total subadult population size of ~6,000 (see AKRF and Popper 2012) to estimate the additional number of untagged subadult sturgeon that may have co-occurred with tagged sturgeon (see AKRF and Popper 2012, for more details). Using this approach, the total abundance of subadult Atlantic sturgeon per unit area was estimated to be ~2,403 subadults/236 hectares/636 h or 0.016 sturgeon/hectare/h. Potential take was then calculated by multiplying subadult abundance by the ensonified area and the duration of pile driving from April through September when subadult sturgeon are known to be in the Hudson River (Bain 1997).

Adults

Because adult sturgeon are not effectively collected by the fishery sampling program, the number of spawning adults potentially affected by pile-driving noise was estimated as a function of the probability of their exposure to the noise. The probability of a migrating adult Atlantic sturgeon encountering the ensonified area becomes greater as the size and duration of the ensonified area increases (assuming sturgeon would not avoid the noise). To calculate this probability, time-weighted ensonified river widths were determined by multiplying the percentage of the river width occupied by the 206 dB re 1 μPa SPL_{peak} isopleths and the number of pile-driving hours during which the isopleths would occur. For example, driving a 1.8-m pile would create a 206-dB isopleth that is ~1% of the river width. The time required to drive 112 of the 1.8-m piles would be ~103 h or 2.6% of the time in which spawning adults occupy the river (i.e., 1 April to 30 September). The product of the driving time and river width metrics equals the time-weighted ensonified river width, which accounts for both the spatial and temporal aspects of construction-related noise and thus the likelihood that adult Atlantic sturgeon would encounter the ensonifed areas. The sum of the weighted river widths divided by the total number of hours in the spawning season for the construction period was used as the probability that a migrating adult would encounter the ensonified areas. To estimate the potential take for adult Atlantic sturgeon, this probability, expressed as a percentage, was multiplied by the number of spawning adults per year (i.e., 288 of 863 or approximately one-third of the adults in the population; Kahnle et al. 2007) to estimate the number of adults that would encounter the ensonified area as they pass through the project area.

4 Sturgeon Take Estimates

Based on the diameter of the ensonified areas for the 206 dB re 1 μPa SPL_{peak} isopleth (1.2-m piles: 12 m; 1.8-m piles: 30–60 m) and the size, number, and timing of piles to be driven, it was estimated that ~35–41 shortnose sturgeon could be exposed to noise levels high enough to cause the onset of recoverable physiological effects during the course of bridge construction. For the sake of parsimony, the take estimate for shortnose sturgeon was used by NMFS (2013) for Atlantic sturgeon (rather than the life-stage specific estimates described in Section 3) on the basis that there are likely fewer Atlantic sturgeon than shortnose sturgeon in the Hudson River.

Although dual-noise criteria (i.e., peak 206 dB re 1 μPa SPL_{peak} and cumulative 187 dB re 1 $\mu\text{Pa}^2\cdot\text{s}$ SEL_{cum}) have been used previously to assess underwater noise impacts and to determine incidental take limits, the SPL_{peak} criterion should be considered the appropriate metric for assessing the potential impacts of pile-driving noise on sturgeon. There are two reasons that the SPL_{peak} criterion is more appropriate than the SEL_{cum} criterion: (1) the existing threshold for the cumulative criterion of 187 dB re 1 $\mu\text{Pa}^2\cdot\text{s}$ SEL_{cum} is considerably lower than the likely threshold for the onset of physiological effects in fishes (see Halvorsen et al. 2012), which results in an overestimate for incidental take, and (2) many fish are likely to avoid pile-driving noise and would therefore not be susceptible to cumulative noise exposure. Recently peer-reviewed experimental studies on the effects of pile driving on small juvenile lake sturgeon (66-mm standard length) showed that the actual onset of physiological effects (e.g., hematoma, ruptured swim bladder) only occurs with sounds with an SEL_{cum} of 207 dB re 1 $\mu\text{Pa}^2\cdot\text{s}$ (Halvorsen et al. 2012). Damage to auditory hair cells is likely to require exposure to even greater sound levels (i.e., as high as 216 dB re 1 $\mu\text{Pa}^2\cdot\text{s}$ SEL_{cum}; Casper et al. 2013). Therefore, the criterion of 187 dB re 1 $\mu\text{Pa}^2\cdot\text{s}$ SEL_{cum} provides an exceptionally conservative estimate of sturgeon take compared with the take that would be estimated if the more scientifically accurate SEL_{cum} of 207 dB were used. Moreover, at sound levels that exceed the current SEL_{cum} criterion, it is expected that sturgeon will avoid the location of pile driving and would therefore not remain long enough to reach an SEL_{cum} (criterion level or otherwise) that would cause the potential onset of recoverable physical injury or mortal injury (see Chapter 67 by Krebs et al.).

Acknowledgments The work reported here was conducted for the New York State Thruway Authority and the opinions expressed are those of the authors and do not necessarily reflect views of the Authority.

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Chapter 69
Automatic Classification of Marine Mammals with Speaker Classification Methods

Roman Kreimeyer and Stefan Ludwig

Abstract We present an automatic acoustic classifier for marine mammals based on human speaker classification methods as an element of a passive acoustic monitoring (PAM) tool. This work is part of the Protection of Marine Mammals (PoMM) project under the framework of the European Defense Agency (EDA) and joined by the Research Department for Underwater Acoustics and Geophysics (FWG), Bundeswehr Technical Centre (WTD 71) and Kiel University. The automatic classification should support sonar operators in the risk mitigation process before and during sonar exercises with a reliable automatic classification result.

Keywords Passive acoustic monitoring • Classification • Detection • Marine mammal database

1 Introduction

The European Defense Agency (EDA) started a 3-years project, "Protection of Marine Mammals" (PoMM), in August 2010 (Knoll et al. 2011a; see Chapter 66 by Knoll et al.). The aim of the project was to protect marine mammals against the impact of active sonar and to maintain the ability to operate active sonar at the same time.

The main component in this project is a comprehensive common marine mammal database. The PoMM database provides knowledge on marine mammals, with a focus on the abundance, seasonal distribution, and density of different species in areas of operational interest for European Navies.

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1.1 The Classifier as Part of the Project

The presented marine mammal classifier should support the sonar operator in the risk mitigation process, monitoring the surrounding area before and during the sonar operation. Therefore, a database of marine mammal vocalizations was included in the PoMM database to train the classifier on the species of interest for European Navies. Furthermore, the automatic classification should help to enhance abundance data of further species in operational areas.

2 Database

The audio part of the PoMM database, also called an audio database, was constructed to empower the contributing nations to store and access their sound libraries and to exchange data in a common format. In addition to the data from the audio database, further recordings from cruises in the North Atlantic and Mediterranean (Knoll et al. 2011b; Ludwig et al. 2011) are available for testing and training purposes.

2.1 Structure

The structure of the audio database was based on audio events, which were combined in a single table and linked to the recordings, further mentioned as objects, and their metadata. This concept allowed labeling multiple and overlapping vocalizations like dolphin whistles and sperm whale clicks.

2.2 Content

The participating nations collected 406 recordings from 36 species with 2,052 labeled events, which were grouped into 10 audio groups (see Table 69.1). These groups summarized the species with a similar repertoire of sounds and similar demands in the risk mitigation process.

3 Classification Approach

3.1 Speaker Recognition

Automatic speaker recognition is the use of a machine to identify a person by his/her voice. Thus, the identification task is comparable to the task of classifying a marine mammal species.

Table 69.1 Content and grouping of the PoMM audio database

Species	No. of events		Group	Species	No. of events		Group
Bowhead whale	19	103	Large baleen whales	Short-beaked common dolphin	23	269	Dolphins
Blue whale	16			Risso's dolphin	18		
Fin whale	25			Fraser's dolphin	6		
Southern right whale	4			Atlantic white-beaked dolphin	4		
North Atlantic right whale	11			White-beaked dolphin	2		
Humpback whale	28			Dusky dolphin	9		
Minke whale	196	199	Small baleen whales	Southern right whale dolphin	1		
Bryde's whale	3			Melon-headed whale	26		
Cuvier's beaked whale	506	507	Beaked whales	Clymene dolphin	5		
Baird's beaked whale	1			Striped dolphin	5		
White whale	25	39	Other odontocetes	Atlantic spotted dolphin	4		
Long-finned pilot whale	12			Spinner dolphin	4		
Narwhal	2			Rough toothed dolphin	1		
Northern bottlenose whale	640	640	Bottlenose whales	Bottlenose dolphin	161		
Bearded seal	9	112	Seals	Killer whale	4	4	Killer whales
Gray seal	83						
Walrus	9			Harbor porpoise	165	165	Harbor porpoises
Harp seal	7						
Ringed seal	4			Sperm whale	14	14	Sperm whales

PoMM protection of marine mammals

The general approach of speaker recognition consists of five steps: (1) digital speech, (2) data acquisition, (3) feature extraction, (4) pattern matching, and (5) decision (Campbell 1997). For human speakers, often the "linear predictor coefficients" were used to model the vocal tract of the speaker. Another approach is to model human sound perception, e.g., with "Mel-frequency cepstral coefficients."

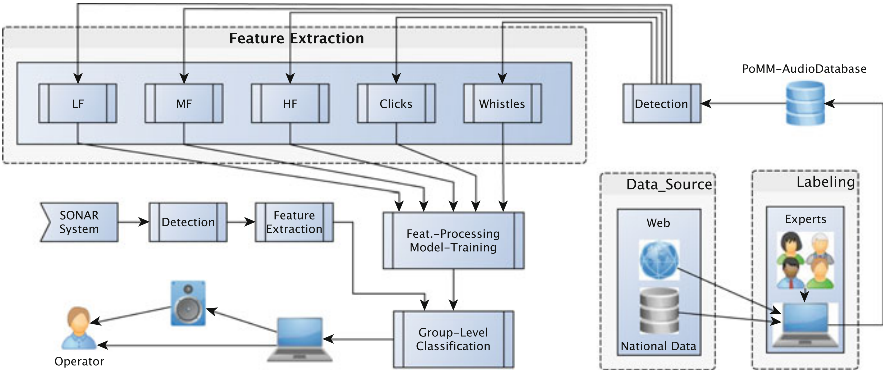

Fig. 69.1 Block diagram of classification system. *LF* low frequency, *MF* midfrequency, *HF* high frequency, *PoMM* protection of marine mammals

3.2 System Design

The classifier is based on the same basic steps as those mentioned in Section 3.1. The main difference for human speaker recognition is the variety of sounds. This requires separate handling of the different sound categories. An overview of the system design is shown in Fig. 69.1.

The classifier is implemented in a self-developed MATLAB framework to meet the needs and demands of the risk mitigation process and to maintain interfaces for further development.

3.3 Arrangement of Frequency Bands

In addition to the variety of sounds, the bandwidth of marine mammal vocalizations is much greater than that in human speech. To achieve an appropriate frequency resolution, the available frequency range (depending on the input system) is divided in different frequency bands for the subclassifiers: low-frequency (LF) classifier (baleen), 0–4 kHz; midfrequency (MF) classifier, 1–10 kHz; high-frequency (HF) classifier, 8–30 kHz; click classifier, 1–48 kHz; and whistle classifier, 0.5–30 kHz. The upper frequency limit of the click classifier is restricted by the training data contained in the audio database.

3.4 Detection and Preprocessing

To detect the parts of interest in the input signal, a detector that is based on a signal-to-noise ratio (SNR) estimate with a relative threshold is used. The noise estimate used for the SNR calculation is also used for a noise reduction of the detected events by wiener filtering. This detection process is applied to each frequency band of the system. The detector is parameterized to maximize the conformance between detection and the labeling process (visual and aural inspection).

3.5 Feature Extraction/Selection

In the training phase, the features are extracted from the events of the audio database, whereas in the classification phase, the features are extracted from the test signal for each detection. The process of feature extraction from underwater sound has to take into account the differences caused by sound propagation. The major items are the frequency-dependent absorption and the dominant multipath propagation. The following sections describe the process band by band.

LF/MF/HF Features

The LF (baleen), MF, and HF subclassifiers are using the same set of features. This set contains features from the frequency and time domains as well as a combination of both. The features and their descriptions can be found in Table 69.2. The idea of this parameterization is to also include the temporal behavior in a simple set of features to achieve maximal robustness. The features are calculated event by event or detection by detection, respectively.

Click Features

Clicks are a unique category of marine mammal sounds and are generated by all odontocetes. Due to this fact, there is a strong recommendation to treat this sound category separately to meet the special needs of these short and broadband sound events.

Table 69.2 Features for the LF/MF/HF classifier

Feature name	Feature description
D	Duration of event, s
p_{crest}	Crest power factor, maximum/mean
f_{cog}	Center frequency, Hz
slope_p/n_f_{cog}	Maximum positive/negative slope of the center frequency over event, Hz/s
rms_time_band	Product of root-mean-square duration and bandwidth
bandw_10 dB	10-dB bandwidth, Hz
band_slope_p/n	Positive/negative slope of 10-dB bandwidth, Hz/s
f_{peak}	Peak frequency, Hz
std_f_{peak}	Standard deviation of peak frequency over time, Hz^2
slope_p/n_f_{peak}	Maximum positive/negative slope of the peak frequency over event, Hz/s

LF low frequency, *MF* midfrequency, *HF* high frequency

Table 69.3 Features for the click classifier

Feature name	Feature description
cl_len	Length of click, ms
sq_len	Length of click sequence, s
f_{cog}	Mean center frequency in sequence, Hz
f_{peak}	Mean peak frequency in sequence, Hz
rms_time_band	Mean product of root-mean-square duration and bandwidth in sequence
bandw_3dB	Mean 3-dB bandwidth in sequence, Hz
ICI_mean	Mean interclick interval in sequence, s
ICI_std	Standard deviation of ICI in sequence, s^2
ΔICI	Maximum difference of ICI in sequence, s

In addition to the features of each single click, there is a lot of information in the sequence in which the click sounds are emitted, e.g., the interclick interval (ICI). Odontocetes often occur in groups so their sounds and click sequences overlap. This impedes the direct calculation of sequence-based features. To cope with this situation, the detected clicks were clustered around their center frequency and their intensity to estimate the click sequences. Further information about this click detection method can be found in Kreimeyer (2012a). Each estimated sequence was parameterized with the feature set shown in Table 69.3. The click detection method was also able to detect and parameterize the short sounds of baleen whales like the thumbs of minke whales.

Whistle Features

Whistles, e.g., emitted by dolphins, are like click sequences, a frequently recorded sound type with an autonomous structure. The detection and frequency estimation method for whistle sounds were described by Johansson and White (2011). This method estimated the frequency of a whistle by minimizing the output of an adaptive notch filter. The frequency estimated by this method was used as a base for a parameterization method described by Kreimeyer (2012b). This method is based on the decomposition of the signal into an amplitude-modulation part, a frequency-modulation part, and a carrier part to achieve the maximal robustness in different sound propagation situations. The used feature set from this method is shown in Table 69.4. This parameterization was also used for all tonal sounds with multiple harmonics, e.g., squeals from killer whales.

3.6 Training

In the training process, the detector (see Section 3.3) was applied to all events stored in the audio database to achieve a best agreement between detections from test data, e.g., from sonar arrays and the labeled training data. These detections were

Table 69.4 Features for the whistle classifier

Feature name	Feature description
f_0	Mean fundamental frequency, Hz
H	Distribution of harmonics
W	Mean weight of harmonics, dB
N_h	Number of harmonics
Δf	Frequency-modulation (FM) range, Hz
f_{min}	Minimum FM, Hz
f_{max}	Maximum FM, Hz
D	Duration, s
η_a	Amplitude-modulation index

parameterized by the methods described in Section 3.4. The following step was the principal component analysis (PCA) of the resulting feature set.

For a reduction in the computation complexity and the dimensions, only the components needed for coverage of the variance of 90% were used. These components were used to train the classification core that can be realized by discriminant classification (linear and quadratic), nearest neighbor's classification, or Gaussian mixture models (GMMs).

4 Classification Performance

The classification performance is not completely evaluated yet. But preliminary simulations showed a reliable behavior of the click classifier for small baleen whales, delphinids, and beaked whales (Fig. 69.2). For the performance of the classifier during the sea trials of SIRENA 2011, a joint research project was conducted by the NATO Undersea Research Centre (NURC) and the Research Department for Underwater Acoustics and Geophysics (FWG), Bundeswehr Technical Centre (WTD 71) in the Ligurian Sea during July-August and October 2011 (see Chapter 79 by Ludwig et al.).

5 Outlook/Future Work

The classification framework works in a MATLAB environment. To embed the classifier into other risk mitigation tools and into the complete risk mitigation process, real-time behavior is required. Therefore, in the first step, the classifier will be ported to C++. Furthermore, the audio database has to be enhanced and reviewed for more homogeneous, reliable training data. Special focus in this review process should be put on the labeling of interfering events, e.g., dolphin whistles and sperm whale clicks, which are overlapping in time and frequency. For achieving an intuitive use by the sonar operators and to approve the classification performance, the

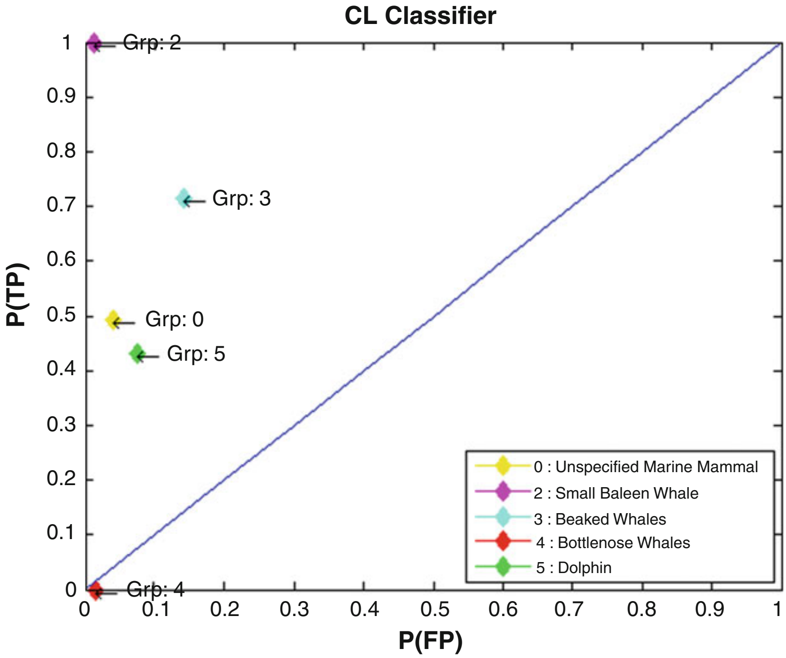

Fig. 69.2 Performance of the click (CL) classifier

results of the different subclassifiers will be combined into a single detection. Until now, the potential of the different used arrays were not used in the classification process, e.g., beam forming can be used to improve the SNR of the input signal. These work steps will be part of the follow-up project PoMM2.

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Chapter 70
Directional Hearing and Head-Related Transfer Function in Odontocete Cetaceans

Petr Krysl and Ted W. Cranford

Abstract The head-related transfer function (HRTF) is an important descriptor of spatial sound field reception by the listener. In this study, we computed the HRTF of the common dolphin *Delphinus delphis*. The received sound pressure level at various locations within the acoustic fats of the internal pinna near the surface of the tympanoperiotic complex (TPC) was calculated for planar incident waves directed toward the animal. The relative amplitude of the received pressure versus the incident pressure was the representation of the HRTF from the point of view of the animal. It is of interest that (1) different locations on the surface of the TPC resulted in different HRTFs, (2) the HRTFs for the left and right ears were slightly asymmetric, and (3) the locations of the peaks of the HRTF depended on the frequency of the incident wave.

Keywords Hearing • Ear • Head-related transfer function • Common dolphin

1 Introduction

The head-related transfer function (HRTF) is a measurement of the transformation for a specific source direction relative to the head and describes the filtering process associated with the diffraction of sound by the torso, head, and pinna. The HRTF is an important ingredient of spatial sound reproduction, and in humans, it has been studied extensively (Wenzel et al. 1993; Wightman and Kistler 1997). The HRTF depends not only on the position of the sound source relative to the listener but also on the features of the listener's external shape and internal anatomy. In this paper, we investigated the HRTFs for distant sources using the finite element method

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applied to a vibroacoustic model of the head of a common dolphin surrounded by seawater and exposed to oncoming planar waves. We computed the received sound pressure level at various locations within the acoustic fats of the internal pinna.

2 Methods

We performed our computational experiments with a CT scan of a *Delphinus delphis* (specimen KDX198). The voxel dimensions for the acquired 3-dimensional (3-D) image were $0.625 \times 0.625 \times 0.625$ mm and the volume consisted of $840 \times 461 \times 524$ voxels.

The vibroacoustic model used in the present study was previously described by Krysl et al. (2008). Its basic principle is the superposition of the known incident displacement (pressure) field and the unknown perturbation displacement (pressure) field. The geometry of the volume of interest is a block divided into volumetric elements (voxels) of identical size and shape. The finite element method is used to discretize the geometry into elements that coincide with the voxels. The dynamics of the scattered wave is integrated in time with the centered difference method. The incident wave provides the forcing, and the scattered pressure wave is subject to absorbing boundary conditions at the boundary of the computational volume to only allow waves to leave. The absorbing boundary conditions in the present implementation are based on the plane-wave approximation.

For computational expediency, the original CT scan was resized to reduce the number of voxels. The cubic voxel dimensions for the 3-D image of the model were $2.5 \times 2.5 \times 2.48$ mm. The computational volume was a 3-D image with dimensions of $210 \times 116 \times 131$ voxels, which were converted to nearly cubical finite elements.

The planar pure-tone acoustic wave was assumed to arrive toward the animal from a source at infinity. The direction toward the source was determined by two angles, azimuth α and elevation β; the normal to the wave front was situated in a plane rotated to the right (positive angles α) or to the left (negative angles α) from the axial-section plane by the horizontal angle α, and then tilted upward (positive angle β) or downward (negative angle β) by the vertical angle β. In the present study, we selected 81 directions for the oncoming sound by varying both the horizontal and vertical angles between $-60°$ and $+60°$ by $15°$. The HRTF was computed for three different frequencies: 5.6, 22.5, and 38 kHz. Receive beam patterns for higher frequencies will be calculated as analysis continues.

The mechanical properties used for bone were Young's modulus, $E = 20{,}000$ MPa; Poisson ratio, $\nu = 0.2$; and mass density, $\rho = 2{,}600$ kg/m^3.

The material properties of the soft tissues were taken as speed of sound, $c = 1{,}620$ m/s; mass density, $\rho = 1{,}087$ kg/m^3; and Young's modulus, $E = 0.124$ MPa for connective tissue; speed of sound, $c = 1{,}520$ m/s; mass density, $\rho = 993$ kg/m^3; and Young's modulus, $E = 0.1$ MPa for muscle; and speed of sound, $c = 1{,}465$ m/s; mass density, $\rho = 935$ kg/m^3; and Young's modulus, $E = 0.065$ MPa for blubber.

Following Norris and Harvey, we used four classes of acoustic fat with a graduated speed of sound, $c = 1{,}450$, 1,430, 1,370, and 1,340 m/s and all with a mass density of $\rho = 937$ kg/m^3 and Young's modulus of $E = 0.065$ MPa.

The properties of seawater were considered as $\rho_w = 1{,}000$ kg/m^3 and $c_w = 1{,}500$ m/s.

3 Results

The results are presented in the form of color-coded plots in Fig. 70.1. The sound pressure level of the received signal is presented for two locations near the surface of each (left and right) TPC. Therefore, four plots are presented for each frequency. The level of 0 corresponds to the received pressure amplitude relative to the amplitude of the incident wave; the negative level corresponds to attenuated signals, and the positive level corresponds to magnified received signals relative to the incident wave.

The dorsal location is in the vicinity of the medial sulcus of the mallear ridge of the TPC (Cranford et al. 2010), the thin bone that is juxtaposed to the malleus of the ossicular chain. The ventral location was selected in the fat body adjacent to the tympanic bone.

4 Discussion

It is of interest that (1) different locations on the surface of the TPC result in different HRTFs, (2) the HRTFs for the left and right ears are slightly asymmetrical, and (3) the locations of the peaks of the HRTFs depend on the frequency of the incident wave.

A carnivorous animal that makes its living using biosonar is required to make decisions about targets (prey) in the region directly forward of the sonar beam on either side of the midline. Evasive maneuvers by the prey that cross the midline present a neurological problem for the predator and solve the inherent left-right ambiguity that arises in the sound field from small differences in acoustic cues. This sort of ambiguity also exists for predators such as barn owls (*Tyto alba*; Knudsen and Konishi 1979). One effective means for making the left-right discrimination acoustically is by creating asymmetry in the transmission beam (Cranford et al. 2014) and/or in the receive beam patterns. This could be accomplished by the sort of asymmetry displayed in Fig. 70.1. As our analysis continues, higher frequency simulations should reveal additional cues to how these animals solve ambiguities in the sonar problem.

Although we attempted to place the virtual receivers at bilaterally symmetrical locations, it should be noted that the anatomic geometry is morphologically asymmetric to some degree. Therefore, it is currently not possible to definitively assign which proportion of the receive beam asymmetry (HRTF) is due to inexact placement of the receivers as opposed to the disparity in morphologic asymmetry.

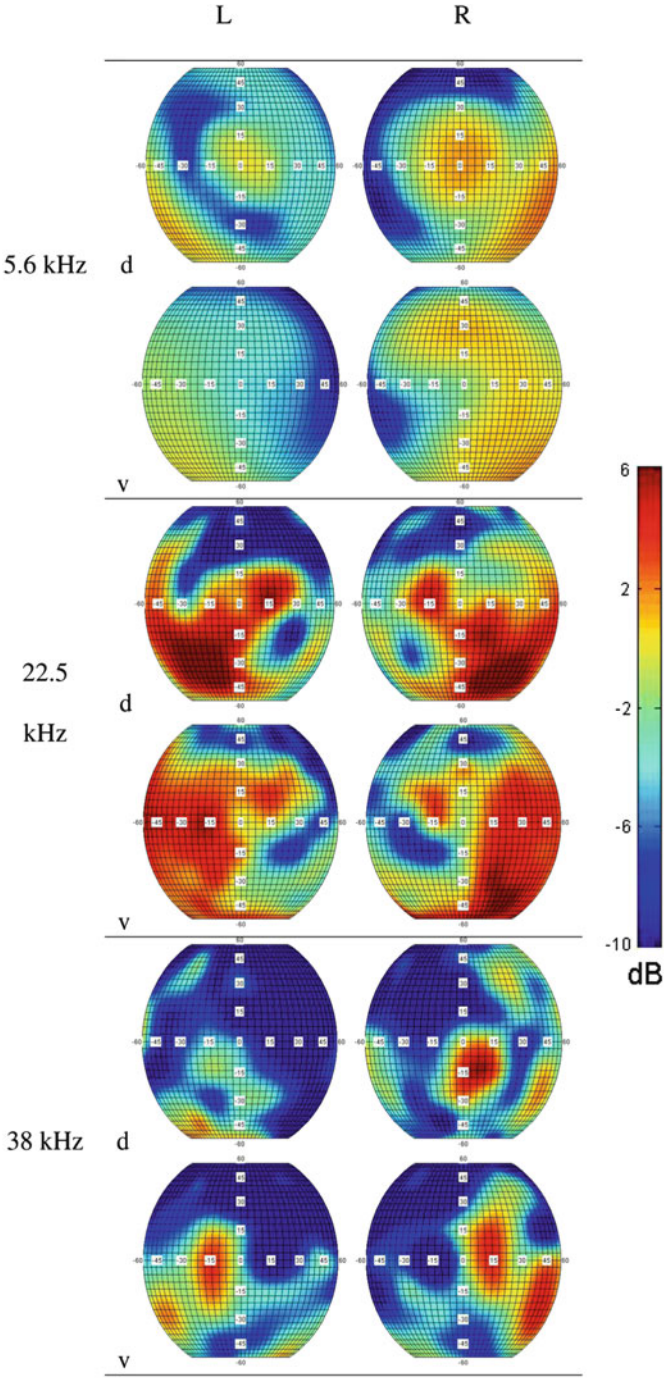

Fig. 70.1 Level of sound pressure received at one of two acoustic fat channels (dorsal [d] and ventral [v]) for the left and right ears. Level of 0 corresponds to the sound pressure of the incident acoustic wave; level >0 corresponds to magnification of the incident acoustic wave

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Chapter 71
Controlled Sonar Exposure Experiments on Cetaceans in Norwegian Waters: Overview of the 3S-Project

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Abstract In mitigating the risk of sonar operations, the behavioral response of cetaceans is one of the major knowledge gaps that needs to be addressed. The 3S-Project has conducted a number of controlled exposure experiments with a realistic sonar source in Norwegian waters from 2006 to 2013. In total, the following six target species have been studied: killer, long-finned pilot, sperm, humpback, minke, and northern bottlenose whales. A total of 38 controlled sonar exposures have been

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conducted on these species. Responses from controlled and repeated exposure runs have been recorded using acoustic and visual observations as well as with electronic tags on the target animal. So far, the first dose-response curves as well as an overview of the scored severity of responses have been revealed. In this paper, an overview is presented of the approach for the study, including the results so far as well as the current status of the ongoing analysis.

Keywords Sonar • Behavioral response • Dose response

1 Introduction: The 3S- and 3S^2-Projects

Widespread concern is felt about the effects that anthropogenic sound such as active sonar can have on marine life. Many forms of marine life rely on the use of sound for feeding, avoiding threats, communication, and navigation; exposure to loud sounds may interfere with these activities. Initial concern about the effects of sonar was increased by incidents involving multiple stranded whales after military sonar exercises.

The use of active sonar is an operational requirement for many navies; alternative technologies enabling detection of underwater objects are not foreseen. “Responsible use” of these systems is necessary, and many navies, including the US Navy, the Royal Norwegian Navy, and the Royal Netherlands Navy, realize that protection of marine life by the responsible use of sonar should be part of everyday routine. However, implementation of specific measures is not easy. Often the necessary knowledge is insufficient, especially knowledge on the sensitivity of marine mammals to specific sonar sounds (e.g., Southall et al. 2007). Research over the last two decades has provided us with a growing understanding of how anthropogenic sound may affect marine life. Our improved understanding shows us that the hearing capabilities of individual animals may be affected in some cases. However, it is much more relevant that marine life may be affected by complex and subtle impacts such as behavioral responses that may influence populations and ecosystems. Moreover, these effects show high variability and may depend on the behavioral context of the animal(s) (e.g., Ellison et al. 2012; Miller et al. 2012). There is an urgent need for the navies to obtain knowledge on these effects, to identify the risk, and tailor the mitigation measures. Implementation of the EU Marine Strategy Framework Directive would require similar knowledge, to determine the magnitude of habitat loss by displacement (see Chapter 24 by Dekeling et al.).

Behavioral response studies (BRSs) or controlled exposure experiments (CEEs) are an important approach for studying the response of animals to potential stressors (Tyack et al. 2003; Tyack 2009). An international and multidisciplinary approach is necessary to carry out this form of research: sea-going experiments are complex and expensive and are more valuable if the results are not tailored to the legal needs of a single country. For this reason, US, Norwegian, Netherlands, and UK institutes

Fig. 71.1 Controlled exposure experiments at sea. Photo by Eirik Grønningsæter/WildNature.no/FFI/3S Project

embarked on the 3S-Project in 2006 and successfully executed sea trials that resulted in a large and already published dataset on a number of marine mammals (killer whales, sperm whales, and long-finned pilot whales; Miller et al. 2011, 2012) and fish (Atlantic herring; Doksæter et al. 2009; Sivle et al. 2012a).

In the follow-on 3S^2-Project, we aimed to expand this dataset to include other marine mammals like northern bottlenose whales and minke whales, animals that can be found in many naval operating areas and are potentially sensitive, so navies urgently need data on the actual risk to populations (Kvadsheim et al. 2011, 2012a). There is also an operational need to verify the efficacy of an often-used mitigation measure, ramp-up (or soft start), which has been done on humpback whales. This paper describes the present status and preliminary contributions of the 3S- and 3S^2-Projects to this complex topic.

2 Executing BRSs or CEEs at Sea

Here we describe the way BRSs/CEEs are executed at sea by the 3S-team (Fig. 71.1). Note that all details can be found in the collection of cruise reports for each field experiment (e.g., Kvadsheim et al. 2007, 2009, 2011, 2012a) that are available on the Internet and also contain the cruise plans and relevant technical documents.

2.1 Logistics

All experiments took place in Norwegian waters. The mother ship of all 3S sonar experiments is the FFI research vessel HU Sverdrup II. From this vessel, small boats can be launched for tagging attempts, photo ID, or observation purposes. The flying bridge of the Sverdrup provided an excellent working platform for visual efforts that were supported with big eyes. The TNO Delphinus system was towed for acoustic detection and monitoring of vocalizing cetaceans. For tagging of the focal whales, we mostly used the DTAG (Johnson and Tyack 2003). For sonar exposure, the SOCRATES (Sonar CalibRAtion and TESting) system is used. The present version (SOCRATES II) can produce source levels up to 214 and 199 dB re 1 μPa at 1 m for frequency bands of 1–2 and 6–7 kHz, respectively. This towable sound source is also used as a prototype system on frigates of the Royal Netherlands Navy (RNLN). The low-frequency transducer is a free-flooded ring (FFR) that is typical for new towed sonar systems now in operational use for submarine detection by many European navies, including Norway and The Netherlands.

2.2 Chronological Description of Events

For executing the controlled sonar exposure experiments, the following steps can be identified. Step 1 is to find the animals (target species). Initially, navigation to the target species was quick by exploiting a network of local Norwegian ships. In many cases, the Delphinus system was capable of detecting whale vocalizations before any visual sighting was reported (see, e.g., Kvadsheim et al. [2009, p. 31] for detection of pilot whales at 25 km or more). The Delphinus system can be towed well below the sea surface and contains two integrated hydrophone arrays: a short 16-element array (up to 40 kHz with beam-forming capability up to 12 kHz) and a high-frequency (up to 150 kHz) 3-element array with a longer (20-m) baseline. For high frequencies, a triplet hydrophone was also added to the system to instantly discriminate between detection of whale calls from left or right (Sheldon-Robert et al. 2008; Kvadsheim et al. 2009, 2012a; von Benda-Beckmann et al. 2010).

Step 2 is to tag the animal(s). Tagging the focal whale is not a simple task and requires the right skills and experience from the tagging team. Traditionally, the DTAG has been placed by a pole with or without a counterweight and cantilever system and attached to the whale with suction cups. With the target species of 3S, this worked well for long-finned pilot, sperm, and humpback whales. After the first 3S-cruise, it appeared necessary to develop a method for launching DTAGs with an air-pressure gun to be able to tag killer whales more easily (LK-ARTS; see, e.g., Kvadsheim et al. 2009). Later it was found that the suction cups were not holding for minke whales. For this, a barbed version of the DTAG was developed (Kvadsheim et al. 2011, 2012a). Before this barbed DTAG became available, one experiment with a minke whale was successfully performed with a (nonacoustic) invasive CTAG (Kvadsheim et al. 2011).

Step 3 was exposure to sound (according to the protocol). The sonar sound exposure was designed in a specific and detailed way. Typical characteristics of the transmitted sound signals are hyperbolic frequency-modulated (HFM) signals in the band of 1–2 kHz (or 6–7 kHz) for 1 s every 20 s at maximum source level of 214 (or 199) dB re 1 μPa at 1 m. For $3S^2$, we focused on the lower frequency band to improve statistical power for just one frequency band. The main aim was to study the response of an escalating sound dose, and this was achieved by ramping up the source level followed by approaching the target whale from a distance of ~3 nm while a smaller boat with observers stayed close to the whales (within 100–200 m). During the exposure, the source vessel (HU Sverdrup II) kept steering toward the animals except for the last 1,000 m when the course was not altered anymore, giving the animals a chance to avoid the oncoming vessel. An emergency stop procedure was in place for hazardous situations as defined in the cruise plans. Different protocols were in place for humpback whales (testing ramp-up responses rather than dose escalation) and for bottlenose whales, where we wanted to remain more stationary to align our method (as much as possible with a towed source) with previous experiments (Tyack et al. 2011; DeRuiter et al. 2013). For bottlenose whales, the dose escalation was achieved by gradually (for 20 min) ramping up the source level. In some cases (minor), deviations from the approach as described above were implemented as documented in the cruise plans and cruise reports. For example, the experiments with some $3S^2$ species were anticipated to take place in more shallow water where there could be more risk of cavitation of the SOCRATES source. For this reason and to remain flexible in most areas, the test frequency bandwidth was decreased to 1.3–2.0 kHz.

In addition to the sonar exposure, there were positive and negative control sounds. The negative control was identical as above but without transmission to test that whales are not responding to the approaching vessel itself. The positive control sounds are the playback of killer whale sounds that potentially are alarming sounds for most target species. Because of their wideband characteristics, the killer whale sounds could not be transmitted by the SOCRATES source but were transmitted by a different transducer (Lubell) at a relatively low level, closer to the source level of killer whales, from a stationary small boat. See the cruise reports and Curé et al. (2012, 2013) for more details and examples.

Step 4 was to observe throughout. Most crucial data were gathered with the recording tags, e.g., dive record and received sound pressure levels. These data were retrieved only after the completion of the experiment when the tag is recovered. However, some data were gathered in real time during the experiment. Tracking of the focal whale was recorded visually by a team of observers, and a formal protocol was followed for recording the characteristics of social context of the focal animal (Visser et al. 2014). These data can be combined later with the recorded data from the tag and the acoustic array so that the surface behavior observations can define any responses to tagging.

3 Status and Preliminary Results

A large part of the data collected is still being analyzed for publication. However, by now also a number of publications have already been issued, and these will briefly be listed below.

At the start of the 3S-Project, we focused on the effects of sonar on Atlantic herring (*Clupea harengus*) because we wanted to discriminate whether killer whales left the Vestfjorden area in response to the sonar or for the lack of prey (Kuningas et al. 2013). During the 3S-2006 cruise, measurements were done in Vestfjorden with overwintering herring (Doksæter et al. 2009) and in 2008 with summer feeding herring (Sivle et al. 2012a). Together with a supporting study with actual navy frigates during all seasons with captive herring (Doksæter et al. 2012), these data supported the conclusion that for the received levels observed (sound pressure level up to 181 dB re 1 μPa) the herring do not respond to the sonar. The only minimal response observed was similar to a response of any other vessel (without sonar). This lack of response to sonar was even more convincing because a clear response was observed to the playback of killer whale sounds. This response was not significant due to the limited number of playbacks, but it demonstrated the suitability of the observation method to identify responses.

With these conclusive results, the herring research was stopped after 2008. In Chapter 25 by Sivle et al., the theoretical consequences of sonar exposure at levels beyond those of the experiments to herring populations are discussed.

For the first phase of the 3S-research with killer/pilot/sperm whales, all data from all experiments were collected and were presented by Miller et al. (2011; see also Table 71.1). Based on these data, the severity of the responses for all experiments were scored by Miller et al. (2012) according to the severity scale as introduced by Southall et al. (2007). A wide spectrum of responses was scored (see Fig. 71.2). Additionally, the diving behavior of these species has been published by Sivle et al. (2012b). Based on this and compared with the dive characteristics of beaked whales, the physiology and risk of decompression sickness (DCS) are addressed in Kvadsheim

Table 71.1 Overview of all experiments for both 3S (2006–2009) and 3S^2 (2011–2013) target species

	Tags	CEE	Killer whale playback
Herring	N/A	12	5
Killer whale	10	4	N/A
Long-finned pilot whale	30	6	6
Sperm whale	10	4	5
Humpback whale	28	10	8
Minke whale	1	1	0/1
Northern bottlenose whale	1	1	0
Total	80	38	24 + 1

CEE controlled exposure experiment, *N/A* not applicable

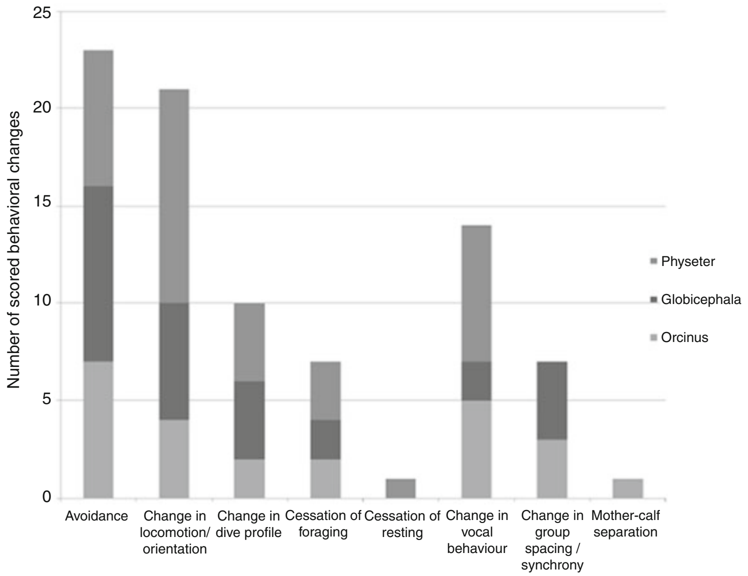

Fig. 71.2 Overview of observed behavioral responses as scored in 47 exposure sessions in 14 unique experiments with the three target species of the 3S Project. From Miller et al. (2012), with permission of Aquatic Mammals

et al. (2012b). Experiments with killer whale playbacks are published in Curé et al. (2012, 2013) for long-finned pilot whales and sperm whales, respectively.

We are aiming to define the dose-response relationships for all species tested and for navies to support the responsible use of sonar. Publications are foreseen for dose-response functions for killer whales (Miller et al. 2014), long-finned pilot whales (Antunes et al. 2014) and sperm whales (Isojuno, Kvadsheim, Tyack, Wensveen, Curé, Lam, and Miller, in preparation). Translation of this kind of information as well as quantifying the impact of sonar exercises was addressed by Ainslie and von Benda-Beckmann (2014) and von Benda-Beckmann et al. (2014) and is discussed in Chapter 150 by von Benda-Beckmann et al. The study on ramp-up resulted in the overall conclusion that in many cases a relatively short period for ramp-up (or soft start) appears to be beneficial for reducing risk of temporary threshold shift/permanent threshold shift. This conclusion is based on a number of assumptions that still need to be verified and depend operational parameters, such as, e.g., the sailing speed of the sonar vessel. The validity of assumed avoidance behavior with ramp-up or soft start, as tested experimentally with humpback whales, is presently under study. Additionally, CEEs were performed with the other $3S^2$ target species: one experiment with a minke whale (a baleen whale) and one with a northern bottlenose whale (a beaked whale).

Apart from the main objectives of the project, many other "by-products" were harvested, such as valuable data describing the overall behavior of cetaceans, improved tagging techniques, and improved technology and procedures for the acoustic monitoring of vocalizing whales.

4 Conclusions So Far

The 3S-Projects have shown that BRSs/CEEs can work well at sea. The project has built an international team with all the skills and technology required. The (sometimes new) operation areas have been assessed successfully. For successful experiments, the tagging turned out to be a bottleneck for some of the species (killer, minke, and northern bottlenose whale). This was partly overcome with new tagging techniques developed during the project but is still a weak link in the overall CEE chain. In all cases, the results feature relatively low sample sizes, and this will always be the case for these complicated and expensive studies. For this reason, the statistics can sometimes be challenging (see Chapter 47 by Harris et al.). Nevertheless, it has been demonstrated that valuable results can be made available in the scientific literature that will provide a proper basis for navies to warrant responsible use of sonar.

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Chapter 72
SOFAR: A New Sound-Acquisition Software Package for Underwater Noise Monitoring

Robert R. Lee, Sofia Patricio, and Samantha Parker

Abstract When monitoring underwater noise, the recording of in situ environmental parameters is a vital supplement to the recording of ambient noise or offshore anthropogenic activities. Although there are some software packages available that have the capability of recording sound at different sample rates using a variety of tools, the set-up configuration and all important environmental conditions recording still rely on the operator. SOFAR, a new sound-acquisition software package, was designed and created to provide an intuitive and streamlined process of recording data along with all the necessary metrics that play a vital role in the data analysis and assessment.

Keywords Acoustic data acquisition • Environmental conditions • Hydrophone • Metadata

1 Introduction

Sound waves propagate far further than light in the sea, and for organisms living in a liquid medium such as fish and marine mammals, hearing is the primary sense for interaction with the environment. There are a wide range of anthropogenic activities that produce artificial noises ranging from shipping to pile driving. It is difficult to quantify the complete impact all these noises have on marine wildlife; even small changes in their behavior may affect survival and therefore can be ecologically significant (Richardson et al. 1995; Mueller-Blenkle et al. 2010). We know that the effects of these additional noises vary greatly, and the ecological impacts can be either physiological (auditory fatigue or trauma) or behavioral (masking and avoidance) depending on the characteristics of the noise source such as frequency and single/transient events, multiple pulse, or continuous exposure (Southall et al. 2007; Mueller-Blenkle et al. 2010; DeRuiter and Larbi Doukara 2012).

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Nowadays, with the development of anthropogenic activities offshore and the recognition of underwater noise as a pollutant by the European Union Marine Strategic Framework Directive (van der Graaf et al. 2012), development license requirements and research studies on underwater noise have increased extensively.

When monitoring underwater noise, the recording of in situ environmental parameters is a vital supplement to the recording of ambient noise or offshore anthropogenic activity (e.g., pile driving, dredging). Such environmental data will be utilized during the analysis process to provide significantly more accurate outputs (International Organization for Standardization 2012). There are many software programs available that have the capability of recording sound at different sample rates using a variety of tools. The creation of a WAV file is one of many required functions; these currently rely on the operator manually recording the set-up configuration and relevant environmental conditions in separate files.

As reliance on accurate ambient, background, and operational noise recordings increases for throughout the environmental impact assessment process and operational planning, an increased level of confidence in the data is required. A new sound-acquisition software package, named SOFAR, was designed and created to provide an intuitive and streamlined process, making high-quality acoustic recordings and logging all relevant metadata.

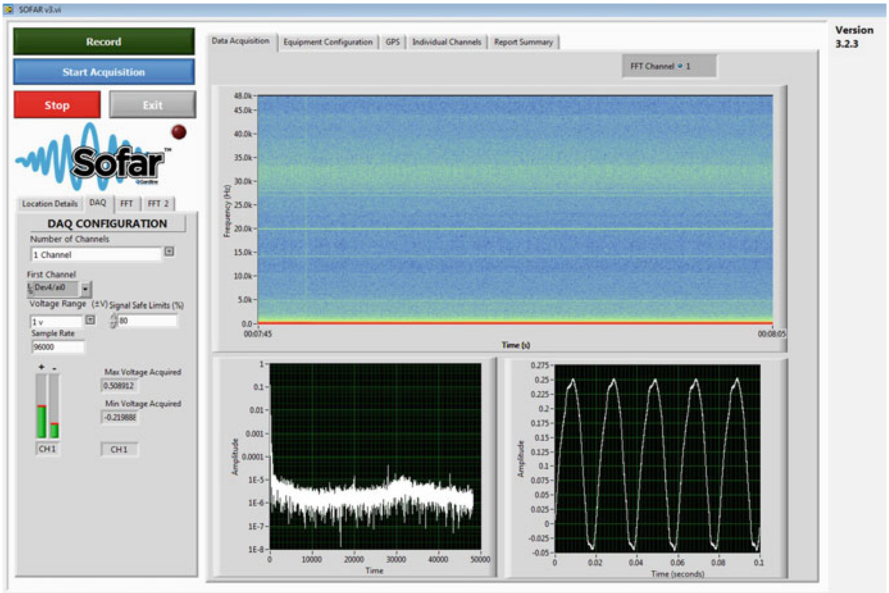
This paper discusses SOFAR's capability to effectively and efficiently record valuable data that could influence the signal for monitoring the underwater noise impact of offshore development projects in preconstruction, construction, and operational phases of the project. A key consideration will be to assess its ability to record sufficient information for a standardized long-term monitoring program while maintaining a suitable user interface.

2 Software Overview

Created with the visual programming language LabView (version 11) and tested with Microsoft Windows (XP and 7), SOFAR is a graphical user interface (GUI) created specifically with the intention of recording ambient and operational underwater noise. Each requires the use of different equipment, but the metrics to be collected in the field remain the same.

The primary function of SOFAR is to use voltages acquired from an underwater transducer to create high-quality WAV files up to 500 kHz. Parameters that have an influence on the recording can be as significant as the WAV file data and therefore are required to be noted. These data include the location, both environmental conditions and anthropogenic activity, equipment used, and recording specifications. Other information regarding the sample period needs to be available for the user to identify artificial noise or clipped recordings quickly. This enables the configuration to be adjusted, and another recording made.

SOFAR has been designed specifically after considering the experience of operators in conducting underwater noise measurements, the shortfalls of existing pieces



Number of Channels: 1 Channel
First Channel: Dev4/ai0
Voltage Range (±V): 1 v
Signal Safe Limits (%): 80
Sample Rate: 96000
Max Voltage Acquired: 0.508912
Min Voltage Acquired: -0.219888

Fig. 72.1 SOFAR data-acquisition interface showing voltages acquired, waveform, and fast Fourier transforms (FFTs)

of software, and knowledge of the difficulties working in what is often a high-pressure environment with harsh time constraints. All these factors have been used to design a piece of software that is intuitive to use in the field, produces high-quality recordings, and ensures that all metadata are added to a Microsoft Access database. With this in mind, SOFAR has been made with a simple tabular design (Fig. 72.1), with options for visualizing real-time data, GPS, equipment configuration, and reporting.

2.1 *Sound Processing*

For accurate noise monitoring, it is essential to use calibrated hydrophones (International Organization for Standardization 2012) and a system to power, amplify, and digitize the signal at an adequate sample rate to avoid aliasing. With this in mind, the decision was made to optimize SOFAR to utilize calibrated Reson hydrophones combined with Reson input modules and National Instruments data-acquisition (DAQ) cards (NI USB-6251 BNC). Combined with SOFAR, the DAQ card successfully recorded from two channels simultaneously at a sample rate up to 500 kHz. This DAQ card also has the flexibility to acquire data at a number of set voltage ranges (±0.1, 0.2, 0.5, 1, 2, 5, and ±10 V).

For underwater operational noise measurements (e.g., pile driving), the time available to take measurements can be very limited. It is often a good methodology practice to take a number of measurements along a transect (Bailey et al. 2010).

Before the commencement of many operations, the duration for the activity is often unknown; therefore, the recordings must be conducted as quickly as possible. To minimize configuration time between sampling stations, where, for example, it may be essential to preserve the computer battery by shutting down the computer, SOFAR initializes with the last sound-acquisition configuration loaded as the default. The voltage range and sampling rate can be modified before sound acquisition; however, these options are unable to be modified once data acquisition has commenced. As data are being acquired, viewing the data through SOFAR gives the operator the opportunity to check the configuration before recording. Once the recording has been started, a WAV file is created in a previously specified location within a folder for each calendar day. To facilitate the writing of files with a large sample rate, each sample is placed in a queue to be written to the WAV file. This creates a buffer that ensures that there is no loss of samples, even at high sample rates.

To help with the postprocessing of the files, the sample rate, voltage range, and channels are automatically logged into a database along with the maximum and minimum voltage values acquired for each channel and the start and end time of the recording.

2.2 Real-Time Sound Visualization

SOFAR has a number of visual tools aimed at helping the user quickly identify if the configuration is suitable and identify any sources of interference.

Waveform Graphs

The amplitude over time waveform graph has been included on the GUI to quickly identify if the correct voltage range has been selected. It is important when acquiring a signal to have this set as close as possible to the actual range being acquired without the signal clipping (i.e., the predetermined voltage range being exceeded). To aid this, the vertical axis scale is automatically set to the voltage range selected. There is a graph representing both channels simultaneously on the "Data Acquisition" tab plus one graph per channel on the "Individual Channel" tab.

Maximum Voltage Acquired

Two further tools in SOFAR have been designed to ensure that the voltage range is optimized for the signal being received; these are both numerical and graphical representations of the extent of the range of the voltages acquired. The graphical representation comes in two forms: a simple meter that displays the percentage of the set range that has been acquired for each channel and a visual warning. The visual warning is activated if the signal acquired is greater than the predetermined safety limit (default 80%). The exceeding of the safety limit is represented by the application background changing to amber, and if the signal clips, it will change to red. When the recording has been completed, the voltage range of the acquired signal is automatically logged in the database.

Fast Fourier Transform

It is essential when taking ambient-noise measurements that there is as little system self-noise being recorded as practicable. This can be identified during a system calibration; however, other avoidable sources of noise, including the vessel's inverter or signals picked up on coiled cables, should be removed before a recording is made. The fast Fourier transform (FFT) graphs present amplitude in the frequency domain, a frequency-spectrum graph. SOFAR has one graph per channel plus a combined graph. There are a range of calculation methods that can be used to create an FFT window, each with its own advantage. Some methods are better suited for identifying narrowband signals and some are more suited to identifying random bands of noise. The decision was made to limit the SOFAR FFT window to the Hanning window because this is suitable for most situations in monitoring marine noise (de Jong et al. 2011). The frequency axis can be changed from a logarithmic to a linear scale and easily identifies bands where an avoidable noise signal may be.

Scrolling Spectrogram

The scrolling spectrogram is the graphical representation of the FFT over time. SOFAR has a spectrogram capable of monitoring one selected channel at a time. There are a number of options for the color scheme to suit the operator, plus a sliding bar that can be used to change the arbitrary z-axis scale (contrast). These display options can be modified while sound is being acquired and are a useful tool for identifying bands of electrical noise with a low signal-to-noise ratio in real time before a recording is made.

The spectrogram has the flexibility to modify the window type (e.g., Hanning or Blackman), the window length, and the frequency bins to accommodate most signals.

2.3 *Equipment Configuration Logger*

During the postprocessing of the data, it is important to know exactly what equipment was used. This is especially important when you have a range of calibrated hydrophones and systems. To ensure that all this information is logged, SOFAR has been designed such that a recording cannot be commenced without first taking note of all the equipment used on a schematic located on the "Equipment Configuration" tab.

The tab also has two free text boxes; the first is to log any damage that may have been sustained, and the second is for additional annotation regarding the setup that is considered influential or important, such as the use of dampeners or subsurface buoys.

Because documenting all the equipment utilized is a time-consuming process, SOFAR automatically assumes that the same equipment will be for subsequent measurements; however, the option is available to update this information at any point if any piece of apparatus is changed or sustained damage.

2.4 GPS Logging

When taking measurements of operational or ambient noise, it is important to know the exact location where the recording was made. Before the development of SOFAR, operators often used GPS waypoints logged into a handheld unit (Garmin eTrex) and then downloaded onto a computer after the survey. For convenience, GPS functionality has been incorporated into the GUI and is optimized to work with a portable USB receiver. These are low-noise, low-cost, and waterproof devices that do not require an external power source. This makes the devices ideal to use on a vessel in environmentally challenging conditions. At the beginning and end of a recording, the GPS location is recorded in the database along with the speed over ground and heading.

As well as the location and heading information, the GPS utility in SOFAR also has the capability to set the computer time to coordinated universal time (UTC) to ensure that data collected from different sources (e.g., autonomous recorder) can be synchronized. This functionality currently only exists for computers using Windows XP.

2.5 Comments

The quality of an underwater acoustic recording is impacted by conditions that may not be constant, such as sea state or the presence of boat traffic (Richardson et al. 1995; Bailey et al. 2010). It is common for this information to be logged manually. To mitigate against the loss of important data (due to incomplete or damaged notes) and to ensure that the same information is logged for each recording, a comments section is included in SOFAR that has drop-down selectors for constants (e.g., sea state) and free text boxes for more variable conditions (e.g., third-party vessel activity).

2.6 Reporting

When SOFAR is first started, an open database connectivity (ODBC) connection is established that connects the software to the Microsoft Access database where all information, with the exception of the WAV file, is stored. This includes any equipment configuration, environmental conditions, and sound-acquisition options. All metadata associated directly with the recording, such as the voltage ranges, sample rate, and file size, are automatically logged. A summary of these data is displayed on the "Report Summary" tab in SOFAR. All the data are available immediately in the database, where it can be linked to other Microsoft Office applications or reporting software such as SAP Business Objects.

3 Conclusions

During the development of SOFAR, user acceptance testing has been ongoing with a selection of operators with varying degrees of experience. It was essential to design a system that had an intuitive GUI that required little configuration to make a recording. Field trials have been conducted recording both underwater ambient and operational noise during the construction of an offshore wind farm with no loss of data. The automatic collection of metadata and data-logging capability of the GUI has proven to be far faster and more reliable than the use of deck forms and subsequent transcribing. The field trials resulted in the identification of areas of improvement that have since been incorporated into the software as an option to load previous equipment configurations and the GPS utility has been simplified.

The intention of the SOFAR design was to produce a tool specifically for acquiring underwater noise measurements and all associated data.

We anticipate the continuous development of the SOFAR GUI as it is utilized more frequently and by a variety of users; however, currently, SOFAR is a valuable tool with which to acquire accurate data for underwater noise measurements.

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Chapter 73
Passive Underwater Noise Attenuation Using Large Encapsulated Air Bubbles

Kevin M. Lee, Mark S. Wochner, and Preston S. Wilson

Abstract Measurements demonstrating low-frequency underwater sound attenuation using arrays of large, tethered, stationary encapsulated bubbles to surround a sound source were compared with various effective medium models for the acoustic dispersion relationship in bubbly liquids. Good agreement was observed between measurements for the large bubbles (on the order of 10 cm) at frequencies below 1 kHz and a model originally intended to describe the acoustic behavior of ultrasound contrast agents. The primary goal is to use the model for designing encapsulated-bubble-based underwater noise abatement systems and to reduce uncertainty in system performance.

Keywords Underwater noise • Anthropogenic noise abatement

1 Introduction

Arrays of large, tethered, stationary encapsulated bubbles have recently been demonstrated to be effective in abating low-frequency underwater noise from anthropogenic sources (Elmer et al. 2012; Lee et al. 2012a, c; Wochner et al. 2012). The technique is considered to be passive because no continuous air supply is needed after the encapsulated bubbles are filled with air. Additionally, the tethered

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bubbles do not generate any additional noise caused by the generation of freely rising bubbles, which are often used in marine pile-driving noise mitigation. The purpose here is to describe how well the attenuation obtained from such bubble arrays can be predicted using effective medium-bubbly liquid sound-propagation models.

Laboratory studies with very thin-walled air-filled latex balloons showed that they behaved acoustically much like free or nonencapsulated bubbles, and sound propagation in a water-filled waveguide containing such bubbles was reasonably well described by Commander and Prosperetti's (1989) effective medium model of bubbly liquids (Lee et al. 2011). Unfortunately, a thicker and more robust encapsulating shell material was required for long-term deployment in the marine environment. Additionally, for predictive purposes, it is important to note that as the thickness and rigidity of the shell material both increase, free-bubble models such as Commander and Prosperetti's (1989) no longer accurately predict the bubble resonance frequency, dispersion, or attenuation due to the influence of the encapsulating shell on the volumetric oscillations of the bubbles.

An effective medium model of sound propagation describing bubbles encapsulated by solid elastic shells was proposed by Church (1995) in the context of ultrasound contrast agents. In a previous laboratory study, resonance frequencies and damping of thick-walled (on the order of 1–2 mm) rubber-shelled balloons were measured and were found to be in good agreement with Church's model predictions (Lee et al. 2012b). Although the ultrasound contrast agents that the Church (1995) model was originally intended to describe are microbubbles, with radii from 1 to 100 μm, it seemed promising that Church's model should equally apply to very large encapsulated bubbles with radii greater than a few centimeters.

As the void fraction of a bubbly liquid increases, it is expected that multiple-scattering effects can become more significant. Like Commander and Prosperetti's (1989) model, the effective medium wave number predicted by Church's (1995) model is equivalent to the lowest order ensemble-averaged wave number predicted by Foldy's multiple-scattering theory (Foldy 1945; Ye and Ding 1995; Feuillade 1996; Hahn 2007; Henyey 1999). In other words, the effects from backscattering interactions between individual bubbles, which are expected to be most prominent near the bubble resonance frequency, are neglected in the lowest order approximations. One modification of Commander and Prosperetti's (1989) model that attempted to account for all higher orders of multiple scattering in an effective medium framework was developed by Kargl (2002). Due to the fact that the encapsulated-bubble arrays intended for use in underwater noise abatement applications have relatively high void fractions (~1% or higher), a new hybrid model was developed, which combined Church's (1995) model for bubbles with shells with Kargl's (2002) method of accounting for radiative interaction between bubbles near resonance (Dolder and Wilson 2013; Lee and Wilson 2013).

Here, we summarize the results from a comparison between underwater sound attenuation data and the various effective medium models (Lee and Wilson 2013) to illustrate which model provides the most accurate attenuation prediction for use in the design of encapsulated-bubble-based noise abatement systems.

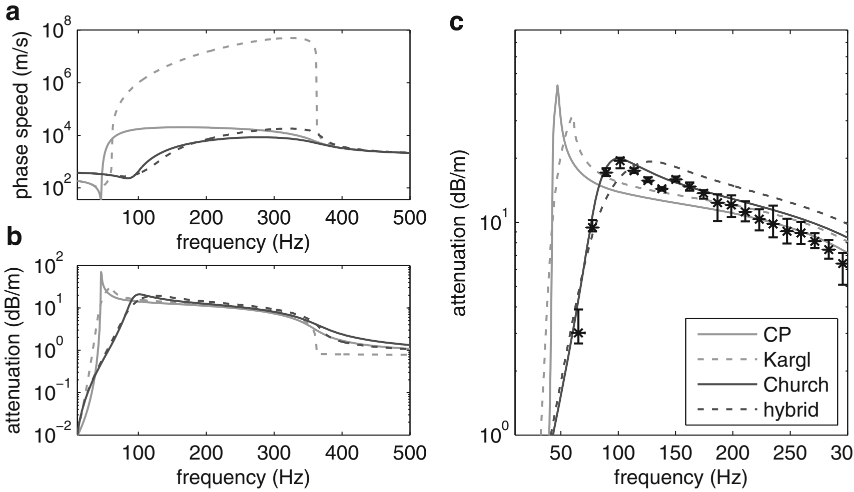

Fig. 73.1 Comparison of phase speed (**a**) and attenuation (**b**) predicted various bubbly liquid effective medium sound-propagation models. Commander and Prosperetti's (CP; 1989) and Kargl's (2002) models were for nonencapsulated bubbles, whereas Church's (1995) model and the hybrid model were for encapsulated bubbles. For each case, the bubble-size distribution was monodisperse, the bubble radius was 8 cm, and the void fraction was 1%. (**c**) Comparison between the attenuation predicted by the various models and the measurements. *Vertical bars*, range of measured values over all of the measurement depths. Modified from Lee and Wilson (2013)

2 Effective Medium Sound-Propagation Models

Various effective medium models for sound propagation in bubbly liquids for bubbles both with and without encapsulating shells are compared. For derivations of these models, see the original publications (Commander and Prosperetti 1989; Church 1995; Kargl 2002; Dolder and Wilson 2013; Lee and Wilson 2013). Here, the phase speed and attenuation predicted by each of the models are compared.

The effective medium wave number (k_m) for each model was computed using the following equations: Equation 35 in Commander and Prosperetti's paper (1989), Equation 6 in Kargl's paper (2002), Equation 27 in Church's paper (1995), and Equation 2 in Lee and Wilson's paper (2013). The liquid medium and shell material input parameters used are also listed in a previous work (Lee and Wilson 2013). The phase speed and attenuation from the various models were computed for a monodisperse bubble-size distribution with bubbles having radii of 8 cm. The void fraction, the concentration of bubbles expressed as a volume ratio, used for the computation was 1%, and the model outputs are compared in Fig. 73.1a, b. The presence of the encapsulating shells on the bubbles causes the bubble resonance frequencies to increase from 45 to 93 Hz compared with the nonencapsulated-bubble case. This effect can be seen in Fig. 73.1a, b, where the phase speed and attenuation curves for the encapsulated-bubble models are shifted in the direction of higher frequencies compared with the nonencapsulated-bubble models. Additionally, a frequency-dependent shear modulus and shell damping were used to model the rubber (Capps 1989), and these have the effect of tempering the abrupt transitions in the phase speed and attenuation that are predicted by the hybrid model for a monodisperse bubble-size distribution. Such abrupt transitions can be seen in Kargl's (2002) nonencapsulated model. It is also worthwhile to note that in the hybrid model, the peak in attenuation is broadened and shifts upward in frequency by ~22% for the chosen model input parameters.

3 Underwater Sound Attenuation Data

Sound reduction using arrays of tethered, stationary encapsulated bubbles was measured at an underwater sound experimental facility in Lake Travis, a freshwater lake in Austin, TX. The measurements and other experimental features are described in more detail in a previous work (Lee and Wilson 2013). The bubbles consisted of rubber-encapsulated air-filled balloons with 1.6-mm-thick shells, which were attached to a submerged steel framework with ~2×2×4 m dimensions. Low-frequency sound (60–500 Hz) was generated using an underwater speaker located near the center of the array of bubbles. The sound pressure was measured outside the bubble array 10 m away from the sound source using a vertical hydrophone array spanning the water column. The lake depth at the measurements site was ~22 m.

The bubbles were nonspherical; however, an effective spherical radius (a) was computed using the measured volume of an individual bubble as an input to the effective medium models, which all treat spherical bubbles. For a given array, the encapsulated bubbles were all filled to identical volumes above the water's surface and adjustment for hydrostatic modification of this bubble volume was not attempted. Three different bubble sizes were used in the experiments, with values of $a = 6.24$, 8.12, and 12.26 cm at a mean deployment depth of 2 m. The void fraction (β) for a given array was estimated using the total number of encapsulated bubbles (N), the mean deployment depth bubble volume (V_b), and the total volume contained within the steel array frame (V_{tot}) with the expression $\beta = N - V_b/V_{tot}$. Three different void fractions were used in the experiment by adjusting the number of bubbles within the submerged framework, with values of β ranging from ~0.5 to 2%.

To estimate sound reduction through the encapsulated-bubble array as a function of frequency from the sound pressure measurements, the spectral levels corresponding to a given array configuration were subtracted from the spectral levels from an experimental case with no encapsulated bubbles attached to the framework. The pressure spectra were computed in 10-Hz bands. To estimate the attenuation, the difference in levels was then divided by the distance from the sound source to the edge of the encapsulated-bubble array. These quantities were then depth averaged to minimize the effects of the spatial dependence of the sound field.

4 Comparison of Data to Model Predictions

For comparison with the attenuation measurements, more realistic bubble-size distributions were used as model inputs as opposed to the monodisperse distribution used in the model calculations in Section 2. To approximate the experimental case, polydisperse bubble-size distributions were used to approximate the variation of the bubble radius with the depth of the bubble array due to hydrostatic pressure.

Comparison of the attenuation measurements for all four models is presented in Fig. 73.1c. The bubble-size distribution corresponds to one with a mean deployment depth effective bubble radius of 8 cm and a void fraction of 0.5%. In the experiment, 35 bubbles were tethered within the framework to achieve this void fraction. For the encapsulated-bubble models, the shell thickness was 1.6 mm, and the material parameters stated in a previous work were used to model the encapsulating rubber shells (Lee and Wilson 2013). Neither nonencapsulated-bubble model properly describes the data below ~100 Hz, which is near the predicted encapsulated-bubble resonance frequency. For the encapsulated-bubble models, the Church (1995) model prediction agrees best with the attenuation data, especially near and below the bubble resonance frequency, and it does not appear in this case that the hybrid model describes the data as well as the unmodified original version does. A potential reason for this discrepancy between the hybrid model and the data is that Kargl's (2002) formulation may not properly take into account multiple scattering or the ways that the Church (1995) and Kargl (2002) models were combined here is inappropriate. Proposed models addressing higher order multiple-scattering effects have been a topic of much debate in the literature (Ye and Ding 1995; Feuillade 1996; Henyey 1999). The measured attenuation appears to be described best by Church's (1995) model, even though that model is expected to underestimate the effects of multiple scattering at a high void fraction, and it is possible that the hybrid version of the model based on Kargl's (2002) theory actually overestimates the higher order multiple-scattering effects.

To test how well the effective medium models account for variation in bubble radius and void fraction, both encapsulated-bubble models were computed for different input parameter sets that corresponded to the various experimental configurations described in Section 3. The comparison between the data and these models is presented in Fig. 73.2. In general, both models predicted that the amount of attenuation should increase with an increasing void fraction and that the frequency range of attenuation should shift to higher frequencies as the bubble radius becomes smaller. The measured attenuation also followed these trends; however, as seen in the previous comparison, Church's (1995) model tended to agree much better with the data near the bubble resonance frequency compared with the hybrid model. Near the bubble resonance frequency, the hybrid model typically underpredicted the measurements by 20% or more, whereas the Church (1995) model prediction is typically within 5–6% of the measured values.

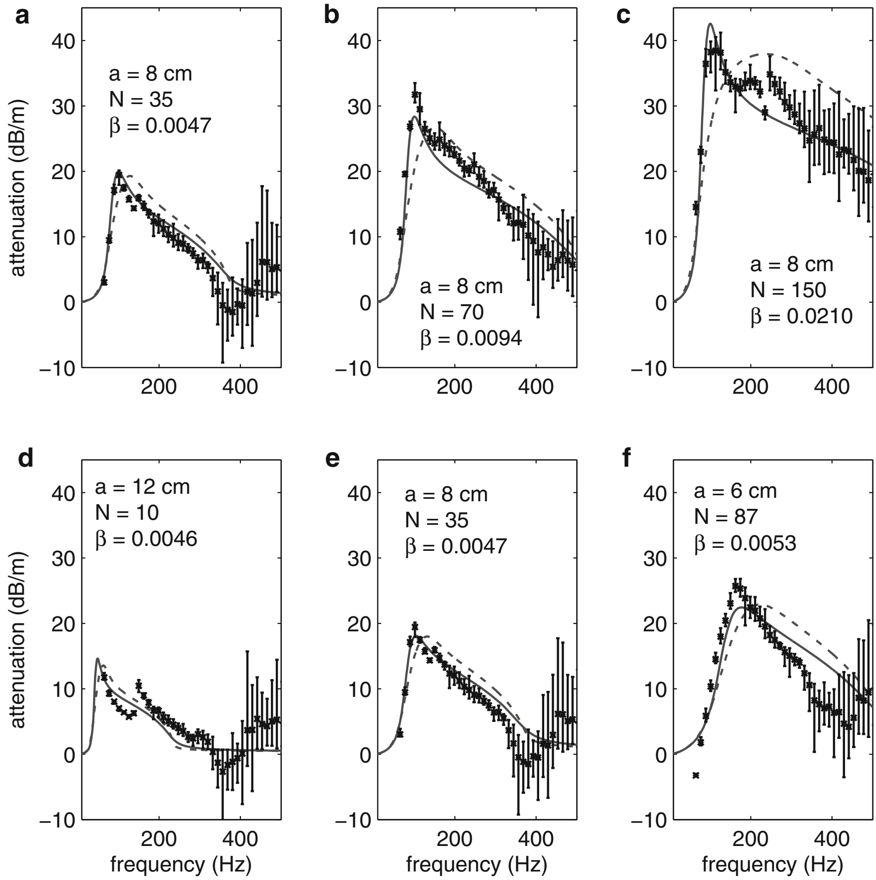

Fig. 73.2 Comparison between the attenuation predicted by the Church (1995) model (*solid line*) and the hybrid Church-Kargl (2002) model (*dashed line*) and the measurements for all the encapsulated-bubble configurations tested. (**a**–**c**) Mean deployment depth bubble radius (*a*) was fixed at 7.96 cm and the void fraction (β) increased from *left* to *right*. (**d**–**f**) Void fraction was fixed at ≈0.005 and the bubble radius decreased from *left* to *right*. Modified from Lee and Wilson (2013)

5 Conclusions

Of the bubbly liquid effective medium sound-propagation models tested, Church's (1995) model, which treats the bubbles as having solid elastic shells, best predicted the measured attenuation. Even though the void fraction was sufficiently large enough to expect corrections for higher order multiple scattering to be significant near the bubble resonance frequency, the hybrid version of the model appears to overestimate the higher order effects, and this model disagrees with the measurements near the predicted bubble resonance frequency.

The use of effective medium bubbly liquid sound-propagation models has potential advantages when it comes to designing underwater noise abatement systems that employ large encapsulated bubbles. For an example of what such a system might look like, see Lee and Wilson (2013), Fig. 1b. Although it is true that models using discrete bubbles, which could be either analytical models using exact multiple-scattering theory (Foldy 1945) or finite-element models using COMSOL or other modeling software, could be used to explicitly design such noise abatement systems, such models typically take more time to set up and more computational effort to use. The effective medium approach described here provides a quicker and more convenient way of predicting the performance of an encapsulated-bubble-based noise abatement system, and this approach is expected to be a highly useful design tool for future noise abatement systems.

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Chapter 74
Measurement of Underwater Operational Noise Emitted by Wave and Tidal Stream Energy Devices

Paul A. Lepper and Stephen P. Robinson

Abstract The increasing international growth in the development of marine and freshwater wave and tidal energy harvesting systems has been followed by a growing requirement to understand any associated underwater impact. Radiated noise generated during operation is dependent on the device's physical properties, the sound-propagation environment, and the device's operational state. Physical properties may include size, distribution in the water column, and mechanics/hydrodynamics. The sound-propagation environment may be influenced by water depth, bathymetry, sediment type, and water column acoustic properties, and operational state may be influenced by tidal cycle and wave height among others This paper discusses some of the challenges for measurement of noise characteristics from these devices as well as a case study of the measurement of radiated noise from a full-scale wave energy converter.

Keywords Underwater noise • Tidal • Wave • Measurement • Tidal energy converter • Wave energy converter

1 Introduction

With the increasing deployment of wave and tidal stream marine energy devices and the plans for deployment of large-scale arrays of such devices, an improved understanding is required of the nature and likely environmental consequences of the

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associated changes in underwater noise due to these systems (Crown Estate 2011; Copping et al. 2013). To date, there has been a limited number of deployment of actual devices and even less measurement of associated underwater noise. In the case of environmental impact assessments, due to the relative infancy of the industry, the primary focus to date has been on construction noise and preconstruction baseline measurements. As these technologies develop for larger scale commercial projects, operational noise will also become a major driver. These measurements are often site and device specific and are conducted as part of the consenting process as commercially commissioned reports. A review of available data for baseline, construction, and operational noise was conducted by Robinson and Lepper (2013) for wave and tidal energy-associated projects. In the case of construction noise sources many include some or all of the following: piling or drilling to fix the device (or its moorings) to the seabed; associated shipping and machinery noise; dredging, blasting, cable burial, trenching, or jetting in soft sediments; rock-cutting machinery in hard seabeds; or rock or concrete mattress laying to protect cables (Faber Maunsell and Metoc 2007; Richards et al. 2007; Patricio 2009; Patricio et al. 2009; Crown Estate 2011; Copping et al. 2013; Robinson and Lepper 2013). These types of noise sources are likely to be relatively short term but with some activities such as piling at relatively high levels occurring. To date, in comparison, operational noise from devices has been rarely measured, with only a few examples from the full-scale prototype systems available (reviewed by Robinson and Lepper 2013). Generally, these examples show that acoustic levels are generally lower than some of the louder construction activities. These levels, however, may occur for much longer periods, i.e., the operation life of the system.

The devices themselves often represent complex distributed sources with a wide diversity of novel mechanical designs and physical distributions within the water column or on the surface (Lepper et al. 2012a). This diversity is often coupled with complex propagation conditions, e.g., shallow water and/or dynamic ambient-noise conditions such as strong tidal flow. These complex influences on the acoustics of a system pose a number of challenges to measuring the radiated noise from these systems (Wilson et al. 2013). This noise will also likely change (periodically in the case of tidal flow) or with a weather dependence for both wave and tidal energy systems.

Because of the wide variety of designs of wave and tidal energy technologies, either in development or under consideration, many may have potential sources of noise unique to their specific design. The potential noise associated with wave and tidal energy devices may include noise generated by turbulence and vortex shedding; noise from hydraulics, joints, and hinges; noise from moorings; the impact of surface waves; rotating machinery (turbine blades, gearboxes, shafts); or the movement of air or water. These sources of noise may have amplitude levels and spectral content that overlaps with the perception capabilities or impact envelopes of a number of freshwater and marine species found in the same environments (Richards et al. 2007; Lepper et al. 2012a).

2 Measurement Methodologies

2.1 Measurement Challenges

Measuring the radiated noise from wave and tidal energy devices poses a number of unique challenges that influence the quality of the available data. These include the environment itself causing self-noise, high levels of background noise, and the wide variety of device types.

Environmental conditions may cause measurement systems to perform badly through actions such as severe wave action (cable heave, impact noise), mooring noise, self-noise of the deployment platform, cable strum, or flow noise. Each of these offers logistical deployment challenges as well as sources of parasitic noise in the acoustic systems. For example, a static receiver in a tidal current can generate substantial flow noise at the hydrophone. Drifting deployments from either boats or, more recently, autonomous recorders (Carter and Wilson 2011; Wilson et al. 2013) can minimize flow noise by minimizing drag of the hydrophone through the water by moving the hydrophone at the same speed as the flow. Drifting boat-based deployments may, however, suffer from additional unwanted noise sources such as vessel self-noise (e.g., generators), heave from wave motion, or wave slap against the vessel hull (Lepper et al. 2012a). The collected data, however, represent a dynamic "snap shot" of the acoustic environment at the time of the drift measurements. The use of drifting deployments from boats (reviewed by Robinson and Lepper 2013) and autonomous drifting recorders (Carter and Wilson 2011; Wilson et al. 2011, 2013) has been used in measurements of a number of tidal energy sites for both baseline and device noise. Antisurge mechanisms have also been used in a variety of studies (Carter and Wilson 2011; Lepper et al. 2012a) to minimize surface motion effects.

To obtain longer term data under different conditions, multiple drift trials must be completed at potentially greater cost. In the case of wave energy sites, boat-based drift surveys and longer term deployments of either surface-mounted or bottom-mounted autonomous recorders have been used (Lepper et al. 2012a; reviewed by Robinson and Lepper 2013) The use of bottom-mounted recorders has the potential advantage that the receiver hydrophone is decoupled from the surface motion, minimizing the noise associated with heave as the hydrophone is dragged up and down due to wave motion. This motion can generate not only flow noise, as with the tidal current (noise due to fluid flow past the hydrophone), but also a low-frequency pressure variation due to variation in hydrostatic pressure, resulting in high-amplitude low-frequency signals. This component can be filtered out, but problems can occur with preamplifier saturation if the levels are high enough before the filter stage.

Bottom-mounted systems have the potential to reduce noise associated with surface motion and platform noise. These systems may, however, suffer from associated flow noise, particularly in strong currents. Potential solutions to flow noise include the use of sonar domes and deployment close to the seabed where flow rates are lower. Either surface-suspended or subsurface floating systems may potentially also experience “cable strum” due to hydrodynamic flow past a hydrophone cable, causing turbulences leading to cable vibration. These vibrations are then seen as parasitic signals in the acoustic data. Techniques such as “vortex shedding” modifications to cables (a spiral winding on cable or “feathered edges”) have been used to minimize these effects as well as deployments close to the seabed and drifting deployments to minimize hydrodynamic flow action.

As well as recording system noise, the background noise in the vicinity of wave and tidal energy sites is often relatively high compared with deep-water ocean sites. This may include substantial surface agitation (wave action) or sediment or bubble transfer/agitation in both wave and tidal sites. It is also likely that device noise will change under differing dynamics. In general terms, in more dynamic situations, i.e., higher hydrodynamic (tidal flow), and/or metrological (sea state), higher background noise levels may also exist. These variations can result in different device-to-background levels to that seen in less dynamic states due to changes in both device-radiated state and background noise levels. These dynamic and often complex relative signal-to-noise ratios under different conditions may also have a strong frequency dependence that poses interesting questions on the relative perception by marine receptors under different conditions and its relationship to collision risk (Wilson et al. 2007).

As with changes in device state and background levels, many wave and tidal energy sites are currently being planned in relatively shallow-water sites close to shore due to favorable energy extraction yield, infrastructure, and cable costs. Bathymetric features, such as beaches, channels, and sand banks, compared with deeper water sites may therefore represent a significant fraction of the water column and have a significant effect on propagation. These propagation conditions may also significantly change with changes in tidal and sea state. Because of this, measured received levels at some distance from a source therefore only represent that source at that distance, in that environment, and at that time. Propagation models are then used to convert the measured received levels to an environmentally independent monopole source level or source level spectrum. This source term can then be used to predict the sound field at other ranges or in other environments (Duncan and Parsons 2011; Robinson et al. 2011). To do this accurately, these models should be capable of accounting for all the key propagation phenomena including (1) interaction with the seabed; (2) interaction with the sea surface; (3) dependence on acoustic frequency (e.g., for absorption in the water and seabed); and (4) dependence on bathymetry. Simple spreading models have been used to propagate the acoustic signals used in a number of studies. Often, the value of the spreading constant is derived from a fit to empirical data. These simple models have been used for predicting propagation between two points in far-field conditions of flat bathymetry, but do not account for all the interactions noted above and therefore should not be used to calculate a source level for the estimation of fields in differing environments. A wide variety of environmentally dependent modeling techniques exist that have been applied to shallow-water environments for industries such as seismic surveys and offshore wind construction. To date, however, only a couple of examples of measured source data from wave and tidal systems have used more sophisticated propagation modeling for source term prediction.

2.2 Measurement Methodologies for Differing Device Types

Measurement methodology challenges are seen due to the environment conditions as outlined in Section 2.1 but also due to the large variety of designs of wave and tidal energy devices. In the case of tidal flow systems, these are often either surface-suspended or bottom-mounted structures distributed through part of or the entire water column. Tidal energy sites are also often in restricted channels, rivers, or sounds of nearby islands, with higher flow rates offering complex propagation environments. Major design types of tidal energy converters (TECs) being tested or under consideration include horizontal axis turbine, vertical axis turbine, and oscillating hydrofoil. In some designs, a significant proportion of the water column is occupied by moving parts, with support structures distributed both horizontally and vertically and swept area radiuses of tens of meters. In the case of wave energy converter (WEC) systems, a large number of potential designs are under development. The major device types can be generalized into a series of categories including attenuator, point absorber, oscillating water column, overtopping device, oscillating wave surge converter, and pressure differential device. These devices are distributed either on the water surface with seabed moorings, on the seabed itself, or through the water column. Arrays of devices may cover many hundreds of meters to potentially many kilometers, with individual devices tens to hundreds of meters in size. A number of studies looking at the development of measurement methodologies have taken place (Lepper et al. 2012a; Wilson et al. 2013), but, to date, no measurement standards exist, making a comparison of data by different researchers difficult (Robinson and Lepper 2013).

3 Case Study: Results for Operational Noise from a Pelamis Wave Energy System

The Pelamis WEC is an example of a large surface-distributed attenuator system that can also be relatively mobile; in this case, it is allowed to move on its mooring to face dominant wave motion. Figure 74.1 shows the measurement methodology used for measurement of a full-scale attenuator system (Pelamis P2, Pelamis Wave Power Ltd.) at the European Marine Energy Centre (EMEC) Billia Croo wave energy test site in Orkney in 2011 (Lepper et al. 2012b). It can be seen in Fig. 74.1 that the placement of autonomous recorder units too close to the WEC could be within a potentially complex near field but too far away where the received levels may be below background levels and therefore difficult to detect. Two recorder systems were placed on each of two orthogonal transects on the beam and end-fire positions. Third-octave and broadband received levels were obtained from the four bottom-mounted autonomous recorders under a range of wave height and sea state conditions. These data and complex propagation loss modeling were used to obtain third-octave band monopole source levels for a virtual center of the device (Lepper et al. 2012b). An example of received level data is shown in Fig. 74.2.

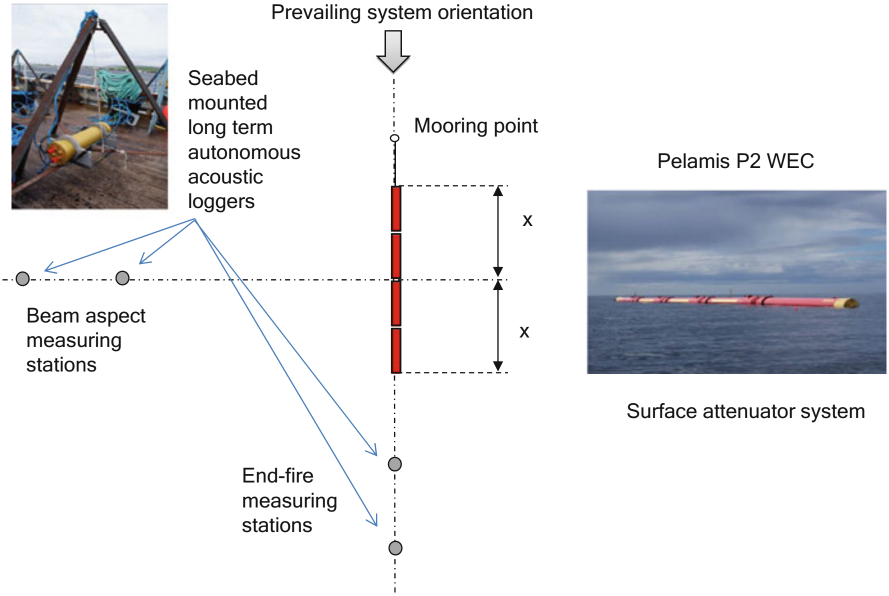

Fig. 74.1 Potential near-field effects from large distributed surface attenuator system. *WEC* wave energy converter. Modified from Lepper et al. (2012a)

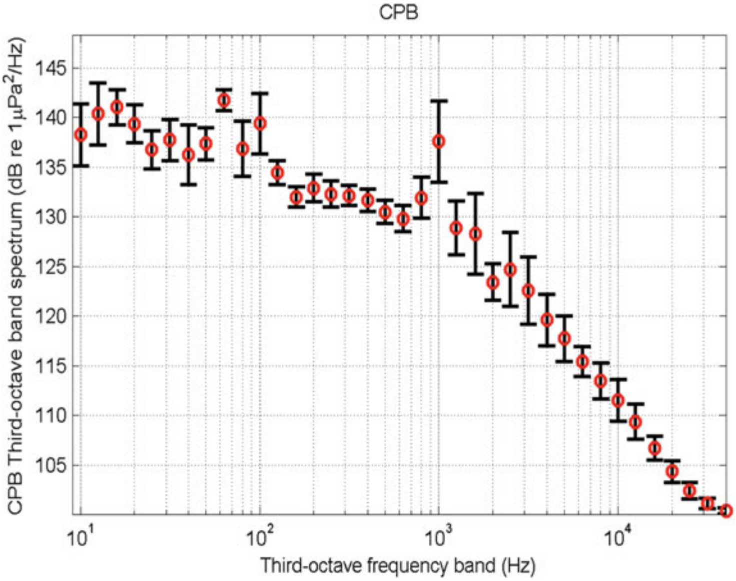

Fig. 74.2 Average 10-min (*red circles*) ± SD third-octave band spectral density received levels from a Pelamis P2 attenuator system at a range of ~256 m. *CPB* constant percentage bandwidth. Modified from Lepper et al. (2012b)

Here the average ± SD third-octave band spectral density received levels for the innermost beam aspect recorder are given. The data were integrated across a 1-s sample window averaged across a 10-min period and show relatively high levels across a broad spectrum due partially to high ambient-noise conditions as well as contributions from the device. The dominant sound sources from the devices can be seen with higher energy levels in the 1-kHz third-octave band (Lepper et al. 2012b).

4 Conclusions

Challenges to the measurement of underwater radiated noise from both wave and tidal stream energy devices include harsh environments (such as fast currents), high background noise, and the wide variety of physical designs to be measured and when compared, all of these factors potentially influence the quality of the available data. To date, comparable measured data are still relatively scarce primarily due to the relatively few number of devices in water at this time and because of the challenges outlined above. These challenges often pose a series of measurement methodology compromises ranging between minimizing platform noise, such as flow noise (e.g., using drifting systems), versus recording device noise under a variety of dynamic environmental conditions (e.g., using long-term static recordings). What data are currently available for a small number of devices suggest levels that are relatively low compared with some construction activities such as marine piling and seismic air gun surveys and are comparable with other anthropogenic noise sources (Robinson and Lepper 2013). This coupled with relatively high ambient-noise and dynamic environments raises questions about collision risk as a topic for ongoing research (Wilson et al. 2007).

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Chapter 75
Likely Age-Related Hearing Loss (Presbycusis) in a Stranded Indo-Pacific Humpback Dolphin (*Sousa chinensis*)

Songhai Li, Ding Wang, Kexiong Wang, Matthias Hoffmann-Kuhnt, Nimal Fernando, Elizabeth A. Taylor, Wenzhi Lin, Jialin Chen, and Timothy Ng

Abstract The hearing of a stranded Indo-Pacific humpback dolphin (*Sousa chinensis*) in Zhuhai, China, was measured. The age of this animal was estimated to be ~40 years. The animal's hearing was measured using a noninvasive auditory evoked potential (AEP) method. The results showed that the high-frequency hearing cutoff frequency of the studied dolphin was ~30–40 kHz lower than that of a conspecific younger individual ~13 year old. The lower high-frequency hearing range in the older dolphin was explained as a likely result of age-related hearing loss (presbycusis).

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Keywords Chinese white dolphin • Odontocetes • Marine mammals • Auditory evoked potential • Noise

1 Introduction

The inner ear of the odontocetes possesses the basic structure and function of an inherently mammalian inner ear (Ketten 1997). The auditory system of odontocetes might reasonably be expected to be subject to impairment or hearing losses in a manner similar to that in humans (Ries 1982). In recent decades, concerns for anthropogenic acoustic impacts on odontocete species have become particularly acute (Richardson et al. 1995; Popper and Hawkins 2012). It follows that hearing loss and its cause in odontocetes is an increasingly important consideration. Although there is some information on the fundamental hearing ability of many odontocete species (Au et al. 2000; Nachtigall et al. 2007; Mooney et al. 2012), the hearing loss has only been investigated and demonstrated in few species in captivity (Ridgway and Carder 1997; Brill et al. 2001; Finneran et al. 2005; Yuen et al. 2005; Houser and Finneran 2006; Houser et al. 2008) or while stranded (Mann et al. 2010). Little is known about the incidence and cause of the reported hearing loss in odontocetes and differences across species and habitat conditions. This paper describes a study on hearing in a recently stranded Indo-Pacific humpback dolphin (*Sousa chinensis*). The hearing of the subject was compared with that of a conspecific younger individual that was recently investigated using the same methods (Li et al. 2012). The comparisons of hearing between the two individuals provide a unique opportunity to understand and interpret the hearing capabilities of the recently stranded dolphin.

2 Materials and Methods

2.1 Subject

The present subject was a male *S. chinensis* that was rescued from stranding in an inland river in Foshan, China, ~200 km upstream from the Pearl River Estuary, on 12 March 2012. On the same day, the dolphin was transported to the rescue center of the Pearl River Estuary Chinese White Dolphin National Nature Reserve, Zhuhai, China (Fig. 75.1a) for further assessment and rehabilitation. The dolphin was 2.43 m in length and 213 kg in mass at the time of the stranding. Analysis of the teeth, particularly the wear on them, and the skin color based on the life history information of the *S. chinensis* (Jefferson et al. 2012) suggested that the dolphin was ~40 year old at the time of the study.

The hearing of the older dolphin was measured on 16 April 2012 and compared with that of a conspecific younger male dolphin ~13 year old that was rescued from stranding on the coast of Beihai Bay, China (Fig. 75.1a), in August 2007 (see details in Li et al. 2012).

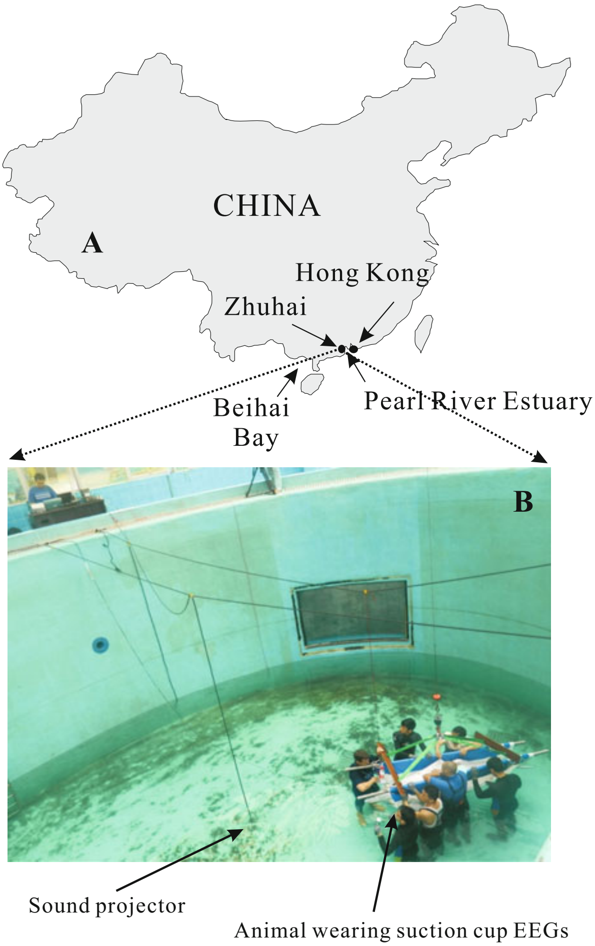

Fig. 75.1 Experimental site and facilities. (**a**) Experimental site in the rescue center of the Pearl River Estuary Chinese White Dolphin National Nature Reserve, Zhuhai, China. (**b**) The dolphin was positioned in a stretcher at the water surface while wearing EEG electrodes attached to the skin by soft silicone suction cups. The sound projector was positioned ~2 m away from the animal's "acoustic windows," where the sound is assumed to travel to the inner ear of the animal

2.2 Hearing Measurement

The hearing measurement of the older dolphin was conducted in the main pool (Fig. 75.1b) of the rescue center using a noninvasive auditory evoked potential (AEP) method. The pool was a kidney-shaped concrete structure 7.5 m in width, 22 m in maximum length, and 4.8 m in depth, filled with man-made seawater. To facilitate a basic medical examination and the hearing measurement, the water depth in the pool was lowered to ~1.3 m before the measurement was performed. The method for sound stimuli presentation and calibration, AEP recording, and hearing threshold determination during the hearing measurement was the same as previously described in Li et al. (2012). Carrier frequencies of the sound stimuli were 5.6, 11.2, 32, 38, 45, 54, 64, 76, 90, 108, and 128 kHz.

The experimental setup for the hearing measurement is shown in Fig. 75.1b. During the hearing measurement, the water depth in the pool was kept at ~1.3 m, and the dolphin was positioned in a stretcher (Fig. 75.1b) in such a way that the dorsal fin and the dorsal surface of the head with the blowhole remained above the water surface while the lower jaw was maintained underwater and open to the sound stimuli throughout the experiment. Three suction-cup electroencephalography (EEG) electrodes were noninvasively attached to the back of the dolphin for the AEP recording. Examination of electrical noise before the hearing experiment confirmed that the electrical noise level for the AEP recording was comparable to that in Li et al. (2012). The background acoustic noise in the experimental pool was recorded before the hearing measurement was made and when the water depth in the pool was ~2.5 m. Measurement and analysis of the ambient noise were the same as previously described in Li et al. (2012).

The resulting audiogram (a function of hearing threshold versus the corresponding stimulus carrier frequency) acquired from the subject was compared with that of the younger dolphin as measured by Li et al. (2012).

3 Results

The measured audiogram of the older dolphin is presented in Fig. 75.2. The lowest threshold (highest hearing sensitivity) of 63 dB re 1 μPa root-mean-square (rms) was measured at 38 kHz, and the frequency region with relatively high hearing sensitivity (within 20 dB of the lowest threshold) was identified between ~8 and 64 kHz for the older dolphin. At frequencies higher than 76 kHz, hearing thresholds of the subject increased steeply, with a rate of ~107 dB/octave, up to 115 dB re 1 μPa rms at 90 kHz.

The power spectrum density of background acoustic noise in the experimental pool (mean ± SD in dB re 1 μPa^2/Hz), which was calculated by performing a fast Fourier transform (FFT) of 10-ms noise windows for each sample and averaged over 1,000 samples, is also shown in Fig. 75.2.

4 Discussion

Figure 75.2 indicates that the audiogram of the older dolphin had a U-shape generally similar to that of the previously investigated younger dolphin (Li et al. 2012) but generally shifted toward lower frequencies and higher thresholds. The hearing

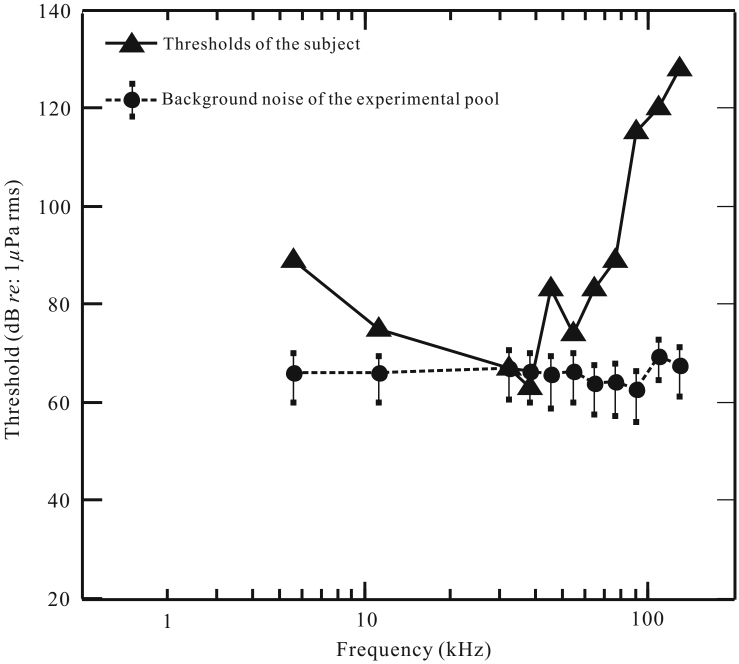

Fig. 75.2 Audiograms of the subject. Values are means ± SD of power spectrum density (in dB re 1 μPa^2/Hz; $N = 1{,}000$ samples) of the background noise in the experimental pool. *rms* root-mean-square

thresholds in the frequency range of 32–76 kHz for the older dolphin were ~10–20 dB higher than those of the younger dolphin (see Li et al. 2012, Fig. 6 and Table 1). However, it was also noted that the background acoustic noise in the two experimental pools inhabited by the older and younger dolphins was obviously different. The background acoustic noise levels in the experimental pool for the older dolphin were ~20–30 dB higher than those in the experimental pool for the younger dolphin, and the power spectrum density of the background acoustic noise for the older dolphin was as high as or higher than the thresholds for the younger dolphin throughout frequencies between 20 and 108 kHz (Li et al. 2012). In the frequency range of 32–76 kHz, the ~10–20 dB higher hearing thresholds for the older dolphin relative to those of the younger dolphin were quite possibly a result of a noise effect of the 20- to 30-dB higher background noise levels. It was very likely that the background acoustic noise in the frequency range between 32 and 76 kHz was audible to the older dolphin and almost certainly masked its true hearing thresholds. At frequencies above 76 kHz, the hearing thresholds of the older dolphin increased steeply, whereas the background acoustic noise levels were rather stable (Fig. 75.2). The steep increase in thresholds, with a threshold of 115 dB re 1 μPa rms at 90 kHz, which is over 50 dB higher than the background noise level and the corresponding threshold of the younger dolphin (Li et al. 2012), might represent a natural feature of the older dolphin's hearing. This suggests that the high-frequency hearing cutoff frequency of the older dolphin was between 76 and 90 kHz, which is ~30–40 kHz lower than that of the younger dolphin (Li et al. 2012). Therefore, although the higher hearing thresholds in the frequency range of 32–76 kHz for the older dolphin might be a result of a masking effect, the older dolphin seemed to demonstrate a high-frequency hearing loss relative to the younger dolphin.

Assuming that the auditory system of odontocetes is similarly subject to impairment or hearing loss as reported in humans and other mammals, hearing loss in odontocetes can be caused by intense chronic noise, transient intense-noise exposure, congenital hearing impairment, physical trauma, infections of the inner ear, ototoxic drug treatment, and presbycusis (Tarter and Robins 1990). Acoustic trauma has been suggested as a factor leading to the stranding of odontocetes (Balcomb and Claridge 2001). Unfortunately, we do not know the noise exposure history of the present subject. During the poststranding treatment and rehabilitation, the older dolphin was not given ototoxic medicines such as aminoglycosidic antibiotics, which might damage the hair cells of the cochlea and result in dolphin hearing loss (Finneran et al. 2005). Considering that the U-shaped audiogram of the older dolphin was generally similar to that of the younger (13-year-old) dolphin but shifted toward lower frequencies and that the older dolphin was estimated to be ~40 years of age, the high-frequency hearing loss of the older dolphin relative to that of the younger dolphin was likely to be the result of presbycusis, which has been previously demonstrated in captive populations of bottlenose dolphins (Ridgway and Carder 1997; Brill et al. 2001; Houser and Finneran 2006; Houser et al. 2008) and a captive false killer whale (Yuen et al. 2005; Kloepper et al. 2010a, b).

Because the older dolphin was a recently stranded animal, it seems reasonable to suggest that prebycusis in the present animal occurred before the animal was stranded and the observed prebycusis exists in old *S. chinensis* in the wild. Because prebycusis is common in human populations (Ries 1982), it should not be surprising that other mammals in their natural habitats also share this development. A false killer whale in captivity demonstrated a concomitant reduction in echolocation discrimination ability with a loss of high-frequency hearing (Kloepper et al. 2010b). It is possible that wild dolphins experiencing high-frequency hearing loss also have compromised echolocation abilities and thus lower survival rates compared with individuals with normal hearing. The stranding of the present subject might be partially ascribed to its potentially compromised echolocation ability with high-frequency hearing loss.

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Chapter 76

Impacts of Underwater Noise on Marine Vertebrates: Project Introduction and First Results

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Abstract The project conducts application-oriented research on impacts of underwater noise on marine vertebrates in the North and Baltic Seas. In distinct subprojects, the hearing sensitivity of harbor porpoises and gray seals as well as the acoustic tolerance limit of harbor porpoises to impulsive noise from pile driving and stress reactions caused by anthropogenic noise is investigated. Animals are equipped with DTAGs capable of recording the actual surrounding noise field of free-swimming harbor porpoises and seals. Acoustic noise mapping including porpoise detectors in the Natura 2000 sites of the North and Baltic Seas will help to fully understand current noise impacts.

Keywords Temporary threshold • Auditory evoked potential • Noise logger • Tagging • Stress

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1 Introduction

The current knowledge about the impact of underwater noise on marine vertebrates in German waters is incomplete. The acoustic impact is therefore one major focus of the German Federal Agency for Nature Conservation (BfN) for sustaining marine and coastal biodiversity. In the framework of different national and international commitments, the BfN organized research on anthropogenic activities in the sea (German Exclusive Economic Zone [EEZ]) in reference to their impact on biodiversity and species conservation. The presented project aims to develop verifiable

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norms for the estimation of the impact of underwater noise on marine organisms by conducting applied research on underwater noise measurements and hearing capabilities of cetaceans and pinnipeds. It involves several research institutions in Germany, Denmark, The Netherlands, the United Kingdom, and Belgium. In distinct subprojects, the hearing sensitivity of harbor porpoises (*Phocoena phocoena*) and gray seals (*Halichoerus grypus*) as well as the acoustic, physical, and behavioral tolerance limits of harbor porpoises to impulsive noise equivalent to pile driving and possible stress reactions caused by anthropogenic underwater noise is investigated. Harbor porpoises and harbor seals (*Phoca vitulina*) have been and will be equipped with acoustic data-storage tags (DTAGs). Underwater noise recorders were/are deployed in the Natura 2000 sites of the North and Baltic Seas to estimate actual noise levels at sea with regard to anthropogenic contribution.

2 Effects of Underwater Noise on Harbor Porpoises

In this subproject, the aim is to verify the sound exposure level (SEL) at which a temporary threshold shift (TTS) occurs in harbor porpoises after an impulsive exposure with a sound exposure level (SEL) of 164 dB re 1 $\mu Pa^2 \cdot s$ by an air gun (see Lucke et al. 2009). Results of the first TTS studies led to a maximum permissible value of 160 dB re $\mu Pa^2 \cdot s$ SEL at a distance of 750 m from the sound source, which has now been implemented for German wind farm permissions. One male harbor porpoise held under human care in the Fjord & Bælt Centre in Kerteminde, Denmark, was used by Lucke et al. (2009). For validation, it is necessary to determine the differences between individuals and to be able to differentiate between the effect of impulsive and tonal stimuli using dose-impact relationships.

The TTS after exposure to single and multiple sound stimuli is measured in free-ranging harbor porpoises temporarily kept in Danish pound nets after being accidentally trapped as well as in porpoises in human care using auditory evoked potentials (AEPs). The methodology is based on the existing knowledge on similar auditory measurements in humans and other marine mammals (e.g., Jewett and Williston 1971; Ridgway et al. 1981; Popov and Supin 1990; Bibikov 1992; Szymanski et al. 1999). So far, AEP measurements have been conducted in several free-ranging and human-care harbor porpoises and data analyses are in process. Animals in the wild have been exposed to sound stimuli with an air gun to test whether a TTS occurs at a SEL of 164 dB re $\mu Pa^2 \cdot s$.

For the evaluation of the immune and stress status in harbor porpoises, levels of stress hormones and the mRNA expression of cytokines and acute-phase proteins were investigated in blood samples of harbor porpoises exposed to different levels of stress during handling or in the wild, rehabilitation, or permanent human care. Blood samples were investigated for catecholamines, epinephrine, norepinephrine, and dopamine as well as for adrenocorticotropic hormone (ACTH), cortisol, metanephrine, and normetanephrine. mRNA expression levels of relevant cell mediators (cytokines interleukin-10 and tumor necrosis factor-α, acute-phase proteins haptoglobin and C-reactive protein, and the heat shock protein HSP70) were measured using real-time polymerase chain reaction. Hormone and cytokine ranges showed correlations to each other and to the health status of investigated harbor porpoises. Hormone concentrations were higher in free-ranging harbor porpoises than in animals in human care (Müller et al. 2013).

To study the influence of anthropogenic noise on harbor porpoises, a high-frequency acoustic data logger (DTAG) has been developed for porpoises (another version will be specially designed for seals). Objectives of this subproject are to study noise levels to which harbor porpoises are exposed and the natural behavior when no ship or other loud sounds are recorded. The results should answer the question about which sounds and at which levels behavioral reactions alternate with baseline behavior. The DTAG will cover a frequency bandwidth of 50 Hz to 160 kHz. The low-frequency response is desirable to record ambient noise but may need to be adjusted upward if excessive flow noise is recorded. It includes triaxial accelerometers and magnetometers and a pressure sensor all sampled at 625 Hz, a programmable release, USB data transfer, VHF and Argos beacons, and memory and battery life for ~2 days (the seal version will record only lower frequencies and will be able to record for several weeks). The device is attached to the porpoise using suction cups. Six deployments on free-ranging porpoises for up to 24 h have been carried out so far.

3 Effects of Underwater Noise on Pinnipeds

Gray seals use acoustic signals for communication purposes both in air and under water (Ralls et al. 1985; Asselin et al. 1993). It can be assumed that the construction of offshore wind turbines or other noise may potentially induce stress, masking, a TTS, or a permanent threshold shift in gray seals. In this subproject, a methodology using earphone inserts was developed and full in-air audiograms for gray seals were collected. The auditory thresholds for gray seals are below 30-dB sound pressure level (SPL) because the results for the frequency range of 4–12 kHz suggest and show strong similarities to in-air behavioral hearing tests of other earless and eared seals above 3 kHz (Ruser et al. 2014).

As described for harbor porpoises in Section 2, a specially designed DTAG for seals will be used to study the influence of anthropogenic noise on harbor seals.

4 Effects of Underwater Noise on Fish

There is growing concern about the effects of human-generated sound on fish. Within this part of the project, a literature review was conducted that included earlier research funded by the BfN (Seibel et al., in preparation). It provided a summary of the possible damage to fish caused by different sound events and focused on the German and adjacent European waters. In conclusion, little is known about the effects of underwater noise on fish and many studies are only published in gray literature.

5 Noise Mapping in Natura 2000 Sites of the North and Baltic Seas

Underwater noise becomes an issue of increasing concern and is more and more discussed as a parameter that could affect marine wildlife in addition to other known environmental stressors. One expression of this concern is the acoustic descriptors published by the European Union as a metric to judge acoustic environmental conditions that still need to be determined and monitored by the states under the Marine Strategy Framework Directive. Three recorders were tested and noise loggers (JASCO AMAR G3) were deployed in the Fehmarn Belt and six other positions in the German Baltic Sea. A first evaluation showed that the different areas have a high influence of anthropogenic noise at lower frequencies, whereas frequencies above 1 kHz are mostly influenced by natural sounds. Trawl shields to prevent deployment losses due to bottom trawls were tested successfully. The deployment of noise recorders in the German Bight (North Sea) was conducted at the moment (July to September 2013). Ten positions are currently deployed in the Sylt Outer Reef. All recorders will be equipped with trawl shields and configured as in the Baltic Sea while, simultaneously, porpoise detectors will measure porpoise occurrence rates.

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Chapter 77
Soundscapes and Larval Settlement: Characterizing the Stimulus from a Larval Perspective

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Abstract There is growing evidence that underwater sounds serve as a cue for the larvae of marine organisms to locate suitable settlement habitats; however, the relevant spatiotemporal scales of variability in habitat-related sounds and how this variation scales with larval settlement processes remain largely uncharacterized, particularly in estuarine habitats. Here, we provide an overview of the approaches we have developed to characterize an estuarine soundscape as it relates to larval processes, and a conceptual framework is provided for how habitat-related sounds may influence larval settlement, using oyster reef soundscapes as an example.

Keywords Estuarine sounds • Acoustic cue • Drifting hydrophone • Bivalve settlement

1 Introduction

Successful recruitment of marine larvae is essential to replenishing populations and maintaining benthic communities (Roughgarden et al. 1988), but larvae are challenged with locating favorable settlement sites after a pelagic phase that can transport them vast distances (Kingsford et al. 2002). The underwater soundscape is a potentially rich source of sensory information for larval organisms during settlement and habitat selection because acoustic signals reflect the physical and biological characteristics of the environment (Montgomery et al. 2006; Cotter 2008; Radford et al. 2010). Compared with chemical and physical cues associated with the substrate on the scale of centimeters, habitat-related sound is a potentially broader scale signal that could facilitate larval encounter with a suitable settlement substrate over meters to kilometers (Montgomery et al. 2006; Lillis et al. 2013).

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Recent studies have demonstrated that coral and rocky reef fish and crustaceans orient and settle in response to habitat-related sounds (e.g., Tolimieri et al. 2000; Jeffs et al. 2003; Simpson et al. 2005; Montgomery et al. 2006; Stanley et al. 2010, 2011), and our work has found a settlement response to oyster reef sounds by oyster larvae (Lillis et al. 2013; see Chapter 30 by Eggleston et al.). Despite this recent progress, the spatiotemporal scales of acoustic variation relevant to larval settlement have not been explored and information specific to the soundscape of estuaries, key settlement, and nursery habitats for a multitude of species is even more limited. Passive acoustic recordings have focused heavily on fish call identification for population and behavioral studies (e.g., Rountree et al. 2006; Locascio and Mann 2008), and previous habitat-related soundscape quantifications have largely consisted of very short-term (5-min), nonsimultaneous recordings that are unlikely to capture the sonic variation to which larvae are exposed during their pelagic phase. Moreover, we are unaware of studies investigating estuarine soundscapes from the perspective of larval dispersal and settlement. Here we highlight several complementary approaches that survey the acoustic characteristics of oyster reef and off-reef habitats in Pamlico Sound, NC, across a variety of spatiotemporal scales that likely match larval dispersal and settlement processes of estuarine invertebrates.

2 Study System

Pamlico Sound is a vast lagoontype estuarine system in the southeastern United States that contains a variety of habitats (e.g., salt marsh, oyster reef, sea grass, soft bottom) that serve as nursery grounds and adult habitats for numerous estuarine-dependent fishes and invertebrates. Oyster reef habitats represent an important functional role in the estuary because they provide a structured biogenic habitat that offers shelter and feeding opportunities for a plethora of resident and transient species (Boudreaux et al. 2006). Because oyster reefs are productive areas that harbor many sound-producing organisms and are patchily distributed habitats sought out by the larvae of many obligate reef dwellers, they are an ideal system in which to investigate habitat-associated sounds and their role in larval settlement. To examine the oyster reef soundscape and compare reef with off-reef acoustic characteristics, we have acoustically sampled a network of ten subtidal oyster reserves located throughout Pamlico Sound (interreserve distances of 20–105 km) since 2010. Simultaneously, we used a reef dweller (oyster) and a nonreef dweller (clam) as study organisms in laboratory and field experiments to examine larval settlement responses to estuarine soundscapes and to investigate the role of habitat-related sound to the larval settlement process (see Chapter 30 by Eggleston et al.).

3 Soundscape Characterization

Previous characterizations of spatiotemporal scales of variation in habitat-associated sounds have involved relatively short-term measurements, such as 2- to 5-min recordings at multiple locations at different times to compare sites or habitat types

(Kennedy et al. 2010; Radford et al. 2010; McWilliam and Hawkins 2013) or 5-min recordings at a single location every hour over a day in different seasons to assess temporal acoustic patterns (Radford et al. 2008). Three such studies have been performed to describe the acoustic patterns of temperate coastal habitats in New Zealand (Radford et al. 2008, 2010), and one has quantified spatial variation in coral reef sound profiles (Kennedy et al. 2010). Our data for Pamlico Sound, however, suggest that the use of a few minutes of data to represent a habitat type or a single day to represent a lunar phase is likely inadequate to characterize the spatiotemporal variation in acoustic spectra of seascapes. During initial acoustic sampling events in Pamlico Sound in June 2010, multiple recordings were made concurrently within the same oyster reserve but at different locations along the reserve boundary (100–400 m apart). These data demonstrated high acoustic variability in both space and time at relatively small scales. For example, over several hours at a single reserve, two hydrophones placed ~400 m apart measured root-mean-square sound pressure levels that varied substantially, with differences of up to 15 dB (Fig. 77.1a). Comparing the power spectral densities for the two stations at two 5-min periods during the

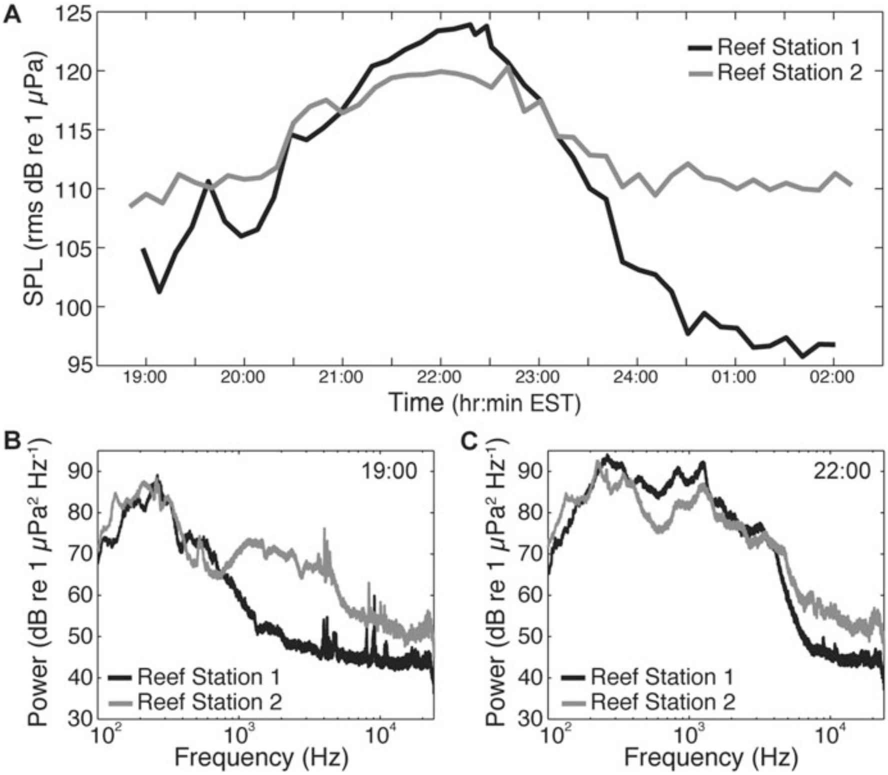

Fig. 77.1 (**a**) Comparison of broadband root-mean-square (rms) sound pressure levels (SPLs) measured overnight on 12 June 2010 at two recording stations at the Clam Shoal oyster reserve. The rms sound level was calculated for 1-min samples every 10 min. Power spectral densities at reef stations for a 5-min sample at 1900 hours (**b**) and a 5-min sample at 2200 hours (**c**). Power spectral density was estimated via Welch's method (Hamming window, 1-s averages with 50% overlap)

deployment (Fig. 77.1b, c) show substantially different spectra. From these initial data, it is clear that making relatively short-term recordings is inadequate to characterize variation in habitat-specific sounds (variation that is likely important to dispersing larvae that might use sound as a settlement cue) and that dramatically different conclusions could be drawn about the soundscape depending on the timing and location of sampling. Based on these results, we added several long- and short-term acoustic-sampling approaches to the overnight stationary recordings (described in Sections 3.1, 3.2, and 3.3) to better characterize the oyster reef and off-reef soundscapes at spatiotemporal scales relevant to oyster larval dispersal and settlement.

3.1 Stationary Hydrophone Habitat-Associated Sound Comparison

In the summer and fall 2010, passive sound recordings were made of subtidal oyster reefs and nearby soft-bottom habitats in Pamlico Sound. Hydrophones were deployed before dusk and positioned ~0.5 m from the seafloor. Hydrophone recording systems consisted of a calibrated omnidirectional SQ-26-08 hydrophone (flat-frequency response 0.03–30 kHz, sensitivity −169 dB re 1 V/µPa; Sensor Technology), and an M-Audio Microtrack II digital acoustic recorder (48-kHz sampling rate, 24 bit) with an external battery pack contained in a surface float. The recorder gain was set at the minimum level during all sampling, and the recorders were calibrated by recording pure-tone sine waves of multiple frequencies produced by a signal generator (Simpson Electric Function Generator 420) and comparing the measured root-mean-square voltage to the derived value (Au and Hastings 2008).

Oyster reefs and nearby soft-bottom habitats (~2–3 km from the oyster reefs) were acoustically sampled simultaneously each month for dusk and nighttime periods around the new moon (±3 days) at three sites spanning the length axis of the estuary. The data indicate that subtidal oyster reef habitats in Pamlico Sound consistently have distinct acoustic spectra, generally composed of significantly more sound in the ~2- to 20-kHz invertebrate-dominated frequency range, compared with the nearby off-reef soft-bottom habitats (Lillis et al. 2014). Based on spectral analysis and comparison with characterized vocalizations of fish common to the area (Sprague et al. 2000), the predominant biological sound sources within oyster reef environments were snapping shrimp (*Alpheus heterochaelis*) and fishes such as the oyster toad fish (*Opsanus tau*), weakfish (*Cynoscion regalis*), and Atlantic croaker (*Micropogonias undulates*). Off-reef areas were generally quieter and devoid of the loud snapping shrimp sounds but often had several-hour-long periods of very loud fish calls, likely due to sciaenid fish spawning events common in Pamlico Sound (Luczkovich et al. 1999, 2008). Unsurprisingly, there was variation in the sound levels among reef sites and within reefs over time, most likely due to differences in sound-producing animal distribution and abundance patterns, with variation in snapping shrimp activity appearing to drive much of the intersite differences. These habitat-specific differences in acoustic characteristics suggest that snapping shrimp are an extremely important soniferous species, with a distribution that contributes substantially to the estuarine soundscape. More information about the general ecology, environmental tolerances, and life history of snapping shrimp would be extremely valuable to the growing field of underwater soundscape ecology.

3.2 Oyster Reef Sound-Propagation Measurements

To investigate the sound emanating from oyster reefs, acoustic surveys were conducted at several oyster reserve sites in Pamlico Sound in 2010 and 2011. Ambient underwater sound was recorded at increasing distances from the oyster reserves in September 2010 and again in June 2011. Two hydrophone recording systems (as described in Section 3.1) were used for each sound-propagation survey; one was placed in the middle of an oyster reserve area and held stationary for the duration of the survey, while a second unit was used to make ~10-min recordings at various distances from the reserve (100, 250, 500, 1,000, 1,500, and 2,000 m). The water depth remained largely homogeneous (3–4 m) over this distance away from the reserve, and the bottom type was consistently sandy mud. The direction of the recording transect at each reserve was chosen based on the bathymetry of the surrounding area to best allow for measurements at distances up to 2 km.

Waveforms from these acoustic surveys were visually inspected using Audacity software to remove transient anthropogenic noise such as boat motors, and simultaneous recordings (from a stationary on-reef station and a given off-reef station) were cut to be the same length, leaving between 4 and 6 min of recording to analyze for each distance. Examinations of the power spectra for the recordings at increasing distances from the oyster reserves revealed that sound levels, particularly in the >2-kHz frequency range, decreased quickly away from the reef and were typically diminished by 15–20 dB within the first 500 m. Although certain reefs were quieter than others, as found in the reef/off-reef comparison, the patterns of sound propagation away from oyster reserves showed a consistent pattern at a variety of spatiotemporal scales, such as among sites across Pamlico Sound (interreserve distances of up to 100 km) and in different years and times of year. These data confirm that the elevated sound levels and frequencies associated with oyster reef habitat have high site fidelity and suggest that habitat-related sound is a good candidate cue to signal close proximity to the desired settlement substrate for reef dwellers.

3.3 Spatiotemporal Variation in the Soundscape Measured via Surface Drifter

To complement the stationary hydrophone acoustic data and to obtain higher spatial resolution measurements with a particular relevance to the planktonic larval phase, we conducted an acoustic survey of oyster reserves using drifting hydrophones.

Drifting acoustic recorders were deployed in August 2011 and again in August and September 2012 at six reserve sites to continuously measure the small-scale changes in sound because an oyster reef habitat is crossed by a passive surface drifter. These experiments were meant to simulate what a planktonic larva might experience as it moves toward and across a reef environment. Drifter units consisted of a free-floating barrel containing an M-audio Microtrack recorder, battery pack, and GPS unit and a calibrated omnidirectional hydrophone (Sensor Technology SQ-26-08 or High Tech, Inc., HTI-96) suspended 0.5 m from the surface. For each drifter trial, two units were deployed ~500 to 1,000 m away from the reserve boundary in the opposite direction of the current. The drifters were released at upstream locations intended to produce a drift that crossed through the oyster reserve. After drifter deployment, the boat was moved an adequate distance so as not to interfere with the recordings while still maintaining visual contact and the motor was shut off. Drifters were observed and collected once they had traveled ~500 m off the downstream edge of an oyster reserve.

Drifters further demonstrated the elevated sound levels and higher frequencies that dispersing larvae might experience as they approach and cross oyster reef habitats (see Fig. 77.2 for an example drifter spectrogram). A very strong reef sound signal was observed at most reserves; however, there were two reefs that were much quieter and with fewer snapping shrimp sounds, and these sites showed a much weaker "reef sound" signal during the drifts (A. Lillis, unpublished data). The drifter data are especially useful in developing a conceptual model of how reef sound could function as a settlement cue, and, in turn, informing laboratory experimental treatments to examine the larval responses to relevant levels of acoustic stimuli (Lillis et al. 2013; see Chapter 30 by Eggleston et al.).

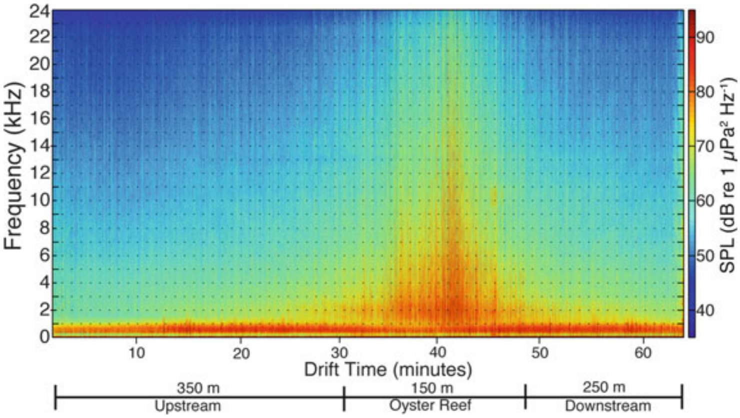

Fig. 77.2 Spectrogram of hydrophone drift across the West Bay oyster reserve (Hamming window, 1-s window with 25% overlap). Upstream, oyster reef, and downstream drift distances are indicated

4 Conceptual Model for Sound as a Settlement Cue

Integrating the results of the soundscape characterization and information of the larval life history and behaviors of our study species, we developed a conceptual framework for how spatiotemporal variability in habitat-related sounds may scale with larval dispersal and settlement to influence settlement outcomes. This conceptual model provides the mechanistic support for how sound could function as a settlement cue and serves as a useful guide for generating hypotheses and determining the relevant acoustic levels for testing them. For example, the results of the stationary soundscape characterization approaches suggest that oyster reefs have, in general, consistently distinct sound characteristics that are highly localized (i.e., a good indicator of close proximity to settlement habitat). The drifting hydrophone surveys, in turn, refined the spatiotemporal scales over which the soundscape can vary during the transport of a planktonic larva, with high-frequency (>2-kHz) constituents increasing substantially as the drifter approached the oyster reef and decreasing as it passed (Fig. 77.2). Given that late-stage oyster larvae can sink or swim at speeds between 0.12 and 0.3 m/min (Hidu and Haskin 1978), we predict that if oyster larvae respond to the oyster reef-associated sounds, they could reach the bottom from the surface (average water depth in Pamlico Sound is 4 m) in far less than the 30 min it took our drifter to cross a relatively small reef. Thus, larvae should have adequate time to respond to reef-associated sound characteristics by moving toward the bottom. After a substrate encounter, oyster larvae are expected to explore the substrate, selecting settlement habitat based on texture, chemical cues, and, potentially, acoustic characteristics. In contrast, we predict that clam larvae move to the bottom in the absence of reef sound, explore the substrate, and settle using substrate (chemical and physical) cues. Our conceptual model demonstrates how sound could play an important role in larval settlement for a weakly swimming larva. Although we illustrate the concept of sound as a settlement cue using oyster and clam larvae (our study organisms), it could be applied to larvae of other reef- and non-reef-dwelling organisms.

5 Conclusions

This work highlights the importance of extensive acoustic sampling over a broad range of spatial and temporal scales to compare habitat-related sounds and better understand the acoustic stimuli to which dispersing larvae may be exposed. We continue to conduct long-term recording time series at reef and off-reef sites to be able to better inform our laboratory and field settlement experiments and, subsequently, apply the results of laboratory and field experiments to the natural environment. This coupling of soundscape characterization and larval ecology shows great promise in improving our understanding of when and where sound may be important in recruitment processes and how anthropogenic noise or the degradation of attractive soundscapes might interfere with these critical ecological processes.

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Chapter 78
Does Vessel Noise Affect Oyster Toadfish Calling Rates?

Joseph J. Luczkovich, Cecilia S. Krahforst, Harry Hoppe, and Mark W. Sprague

Abstract The question we addressed in this study is whether oyster toadfish respond to vessel disturbances by calling less when vessels with lower frequency spectra are present in a sound recording and afterward. Long-term data recorders were deployed at the Neuse (high vessel-noise site) and Pamlico (low vessel-noise site) Rivers. There were many fewer toadfish detections at the high vessel-noise site than the low-noise station. Calling rates were lower in the high-boat traffic area, suggesting that toadfish cannot call over loud vessel noise, reducing the overall calling rate, and may have to call more often when vessels are not present.

Keywords Soundscapes • Soniferous fishes • Fish sounds • Vessel noise • North Carolina • Pamlico Sound

1 Introduction

The midshipman and toadfish family (Batrachoididae) is one of the more vocal groups of fishes, being found in all the world's oceans. Sound production and reception is very important to toadfish during their mating period. Male *Opsanus tau*

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(oyster toadfish) produce sounds during courtship and nest guarding (Gray and Winn 1961; Fine 1978; Amorim and Vasconcelos 2008; Rice and Bass 2009). Sound production occurs more often at night than during the day (Thorson and Fine 2002). The metabolic costs of sound production are important (Amorim et al. 2002) because the *Opsanus tau* muscle is among the fastest vertebrate muscles ever measured (Skoglund 1961; Rome and Lindstedt 1998) and muscle fatigue during long periods of courtship and calling have been documented (Mitchell et al. 2008). In addition, *Tursiops truncatus* (bottlenose dolphin) predation on *Opsanus tau* guarding eggs during the mating period is significant and the dolphin may use the mating sounds to locate the toadfish (Barros and Randall 1998; Gannon et al. 2005; Dunshea et al. 2013). Finally, it has been shown that shipping noise interferes with a related toadfish species *Halobatrachus didactylus* (Lusitanian toadfish) hearing (Vasconcelos et al. 2007), with up to a 30-dB loss in sensitivity at certain low frequencies, suggesting that females may be unable to hear males in some situations (masking from ship noise). Thus, an important question is how does vessel noise impact the calling rates of *Opsanus tau* males? Do they reduce calling rates in noisy environments, move to locations with less noise to make mating calls, or increase calling rates or sound pressure levels to continue to be heard by females?

In this paper, we investigated these questions by comparing the calling rates of male *Opsanus tau* (oyster toadfish) in two locations, one near a noisy boat channel (Neuse River Junction [NRJ] site near the Intracoastal Waterway) and one in a remote location (Pamlico Middle Sound [PMS] site) in Pamlico Sound, NC. We hypothesized that fish would call more often in quiet periods between vessel passes, and the calling rates would be higher in the noisy environment because the males call more often to be heard over the noise.

2 Methods

2.1 Passive Acoustic Recorder Deployments

We used mobile estuarine observatories based on a stainless steel tripod frame (called instrumented tripods or ITPods). The ITPods are rapidly deployable, mobile estuarine-observing stations for short- and long-term studies in NC estuaries that have passive acoustic data loggers that record variations in fish sound pressure levels while also measuring physical parameters (temperature, salinity, dissolved oxygen, water and air weather conditions). With these data, we can measure the short- and long-term variations in sound levels that indicate toadfish spawning and study how sound production correlates with environmental conditions (vessel noise, physical measures that are correlated with spawning). The components of these ITPods include a passive acoustic digital recorder (long-term acoustic recording system [LARS], Loggerhead Industries, Inc.) that records low- and midfrequency sounds (<10 kHz) on a digital file (the LARS records 10 s of ambient sounds to a WAV file on a 2-GB compact flash card from a single HTI model 96-min hydrophone at 15-min intervals) along with temperature, salinity, oxygen, and turbidity levels using a Hydrolab Surveyor water quality meter. A Nortek Aquadopp acoustic Doppler profiler (ADP) was used for measuring water depth, tidal variations, currents, and waves, a Nortek Vector for seabed elevation changes, and an OBS for near-bed turbidity measurements. An ITPod was deployed beginning in April until November 2006 at the mouth of the NRJ site near the Intracoastal Waterway. Another ITPod was deployed in April until November 2008 at the PMS site. We deployed and recovered ITPods every 45 days. On each of these recovery and redeployment days, data were downloaded, instruments were cleaned and calibrated, and batteries were replaced. Data used for this work focused on recordings made at the start of the *Opsanus tau* mating season (June and July).

2.2 Analysis of Sound Recordings

We used Raven 1.4 with a band-limited energy detector trained for *Opsanus tau* mating calls (boat whistle or “boop” sound). Band-limited energy detectors compute a background noise level and look for sound energy variations in a defined frequency band that exceeds the noise threshold by a given signal-to-noise parameter. These detectors are good when looking for characteristic calls of a species with a known duration in a frequency band. The toadfish boat whistle is such a call, and our detectors used the temporal and spectral parameters shown in Table 78.1. The band-limited energy detector and these parameters are explained in the Raven user manual (Charif et al. 2010). Two different detectors in Raven were used, varying only by the minimum occupancy or the minimum percent of the time during a sample window in which the sound level exceeded the signal-to-noise threshold and met the other criteria. Both detectors were tested for accuracy by running them against a test set of data from the NRJ site in June 2006 and the PMS site in June 2008, with an analyst listening to the recordings and scoring accuracy. The prototype band-limited energy detector for toadfish boops (detector 0, with 10% minimum occupancy) had a true positive rate (true positives detected/total) was 90.9% and the

Table 78.1 Parameters used in the band energy threshold detectors used in Raven

Parameter	Detector 1	Detector 2
Minimum frequency (Hz)	15	15
Maximum frequency (Hz)	250	250
Minimum duration (s)	0.09288	0.09288
Maximum duration (s)	0.89977	0.89977
Minimum separation (s)	0.09288	0.09288
Minimum occupancy (%)	50	70
Signal-to-noise threshold (dB)	10	10
Noise estimate block size (s)	3.00118	3.00118
Noise estimate hop size (s)	0.99846	0.99846
Noise estimate percentile (%)	50	50

false positive rate (false positive detected/total) was 6.9% for 1-s intervals from 250 10-s recordings in the test run on May 2006 NRJ data. However, this prototype band-limited energy detector was influenced by background noises from vessels and many false positives occurred when *Cynoscion nebulosus* spotted seatrout were actively calling in June and July. Thus, two different slightly detectors (identical in all parameters except that detector 1 used a 50% occupancy criterion and detector 2 used a 70% criterion) were run on each set of data to minimize the false positives from biological and anthropogenic background noises. Representative sounds were listened to and spectrograms were examined to display fish sounds and vessel noise.

3 Results

Opsanus tau oyster toadfish boat whistles were heard and detected at both the NRL (noisy) site and the PMS (quiet) site. In addition, *Cynoscion nebulosus*, spotted seatrout, and *Bairdiella chrysoura*, silver perch (both in the family Sciaenidae), were also heard on both sets of recordings. Many vessels were heard at the NRJ site but few or none at the PMS site (Fig. 78.1). Overall, sound levels of fish choruses and vessels were higher at the NRJ site. The calling rate, as judged by the number of *Opsanus tau* toadfish boat whistle detections in a 37.5-h period, was lower in the quiet PMS site (Table 78.2). Using detector 1, with 50% occupancy parameter, 600 detections were made in 300 10-s recordings, an average of 2 boat whistles per 10-s recording or 12/min. In contrast, using this same detector, only 381 boat whistles were detected in the NRJ recordings, an average of 1.27 boat whistles per 10-s recording or 7.6/min. Using detector 2, with 70% occupancy parameter, 350 detections were made in 300 10-s recordings, an average of 1.2 boat whistles per 10-s recording or 7/min. In contrast, using this same detector, only 185 boat whistles were detected in the 300 NR J recordings, an average of 0.61 boat whistles per 10-s recording or 3.7/min. This lower rate could be due to disturbance from vessel noise, which overlaps in frequencies that the fishes make. Vessel noise often dominated the sound spectra from 0 to 10 kHz in a single 10-s recording during which no boat whistles were detected or heard on the recording. Vessel noise is apparently masking the sounds of nearby males calling, and this results in a cessation of calling when a vessel passes, as clearly seen in Fig. 78.2.

4 Discussion

The rate of calling by male *Opsanus tau* was lower in the noisy NRJ site near the Intracoastal Waterway relative to the quiet PMS site. *Opsanus tau* males may be influenced by vessel noise in a negative way, shutting down until the vessel passes. However, *Opsanus tau* continue to call when a vessel has passed by and may briefly attempt to make up for the lost time by raising calling rates. However, with

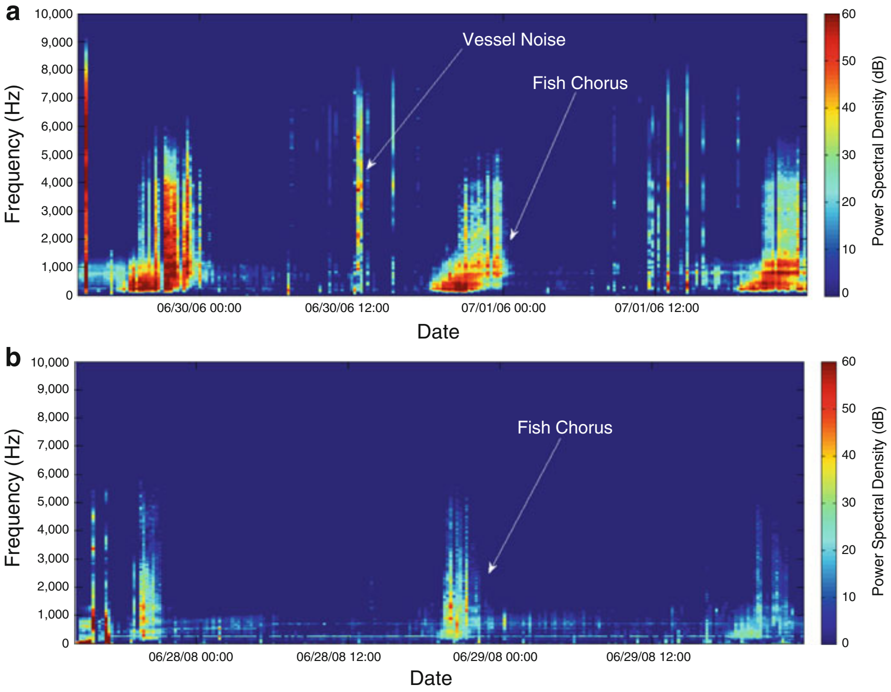

Fig. 78.1 Composite spectrograms of sounds from noisy Neuse River Junction site starting on 30 June 2006 (**a**) and quiet Pamlico Mouth site on 27 June 2008 (**b**). Recordings were taken at a duty cycle of 10-s recorded sound every 15 min for 57.6 h or 2.4 days. Fish choruses are *red* and *yellow regions* under 1 kHz, with peaks extending to 8 kHz; bright vertical bands at Neuse River site are vessels passing, which dominate the 10-s sound recordings and are often broadband at 0–9.5 kHz. *Opsanus tau* boat whistles occurred both day and night, but the *Cynoscion nebulosus* (spotted seatrout) and *Bairdiella chrysoura* (silver perch) Sciaenidae choruses (two dark regions) were loudest after sundown, occurring nightly through the month of June and July

Table 78.2 Detection of *Opsanus tau* (oyster toadfish) using band-limited energy detectors 1 and 2 at Neuse River Junction (noisy) and Pamlico Middle Sound (quiet)

Time Period	Detector	Neuse River Junction	Pamlico Middle Sound
June 27–28 (150 10-s recordings)	1	180	309
June 28–29 (150 10-s recordings)	1	201	291
Total		381	600
June 27–28 (150 10-s recordings)	2	90	189
June 28–29 (150 10-s recordings)	2	95	161
Total		185	350

enough noise-induced disturbance, the overall calling rates are lower, with an unknown impact on the mating success of these fish. Calling rates are less than the maximum that has been observed for this species of toadfish as described by Winn (1972) and Fish (1972), which is as high as 80 boat whistles in a 5-min period

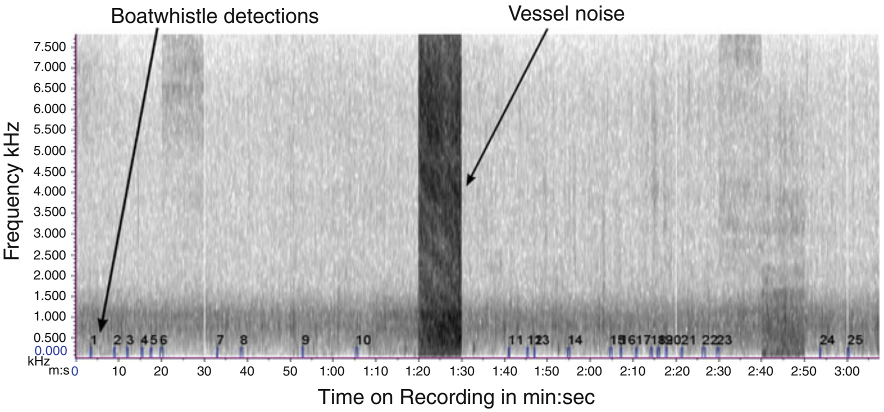

Fig. 78.2 Spectrogram composite from eighteen 10-s recordings taken at 15-min intervals showing detection of *Opsanus tau* oyster toadfish using the band-limited energy detector at the Neuse River Junction (noisy) site. *Blue lines* indicate a toadfish was detected at that time. Dark band is a large vessel that passed by the recorder at 1 min 20 s. Divisions in the spectrogram indicate 10-s recording segments

(or 16 boat whistles/min). It is also possible that there were more toadfish in general at the quiet site, contributing to the higher calling rates. The detectors we used produced some false positives, especially when *Cynoscion nebulosus* (spotted seatrout) were calling at night, so the rates reported here may actually be lower. Competition with the *Cynoscion nebulosus* sounds may cause disturbance as well because the *Opsanus tau* toadfish must be heard by a female over that call in the background. We did not attempt to enumerate the toadfish present at each location and were not able to tell individual fishes apart in the recordings. In summary, this observational study is in need of experimental verification using controlled vessel sound levels and a known number of *Opsanus tau* individuals present, with calling rates measured before and after vessel-noise exposure. Such experiments are underway at the current time.

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Chapter 79
Comparison of PAM Systems for Acoustic Monitoring and Further Risk Mitigation Application

Stefan Ludwig, Roman Kreimeyer, and Michaela Knoll

Abstract We present results of the SIRENA 2011 research cruises conducted by the NATO Undersea Research Centre (NURC) and joined by the Research Department for Underwater Acoustics and Geophysics (FWG), Bundeswehr Technical Centre (WTD 71) and the Universities of Kiel and Pavia. The cruises were carried out in the Ligurian Sea. The main aim of the FWG was to test and evaluate the newly developed towed hydrophone array as a passive acoustic monitoring (PAM) tool for risk mitigation applications. The system was compared with the PAM equipment used by the other participating institutions. Recorded sounds were used to improve an automatic acoustic classifier for marine mammals, and validated acoustic detections by observers were compared with the results of the classifier.

Keywords Passive acoustic monitoring • Marine mammal • Detection • Classification • Active sonar

1 Introduction

Several atypical mass strandings of beaked whales (Ziphiidae) in recent years added to the evidence that maybe these were caused by coinciding naval exercises involving midfrequency active (MFA) sonars (e.g., Southall et al. 2007; Zimmer and Tyack 2007; D'Amico et al. 2009; Tyack et al. 2011). These strandings demonstrated that exposure to active sonar can affect marine mammals negatively and that,

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in particular, beaked whales are sensitive to MFA (e.g., Tyack et al. 2011). This has driven a need to develop methods for mitigation to reduce the risk. On the other hand, the use of active sonar is still essential for the Navies. During the last several years, research for marine mammal risk mitigation was carried out and new valuable knowledge on that topic was achieved. Besides a better understanding of the behavior patterns, physiological characteristics, habitat preferences, and predictions for various species, tools for the acoustic online detection of marine mammals are essential to improve risk mitigation measures.

The aim of the SIRENA 2011 research cruises was to perform a visual and expanded acoustic survey for further implementation in habitat modeling for risk mitigation related to active sonar use and to deploy and compare passive acoustic monitoring (PAM) technologies for marine mammals. With that cooperation, conducted and coordinated by the NURC (Hughes 2011), we had the opportunity to use and test the recently obtained Research Department for Underwater Acoustics and Geophysics (FWG) hydrophone array onboard the research vessel (RV) Alliance and to compare it with the acoustic devices deployed by the other participants. Furthermore, observer-based and validated acoustic detections were compared with an automatic acoustic classifier (Kreimeyer 2012; also see Chapter 69 by Kreimeyer and Ludwig).

2 PAM Systems

During the SIRENA 11 cruise, three different towed acoustic devices were used to detect and, if possible, localize and classify marine mammals in the area: the FWG hydrophone array, the compact PAM (CPAM) array from the NATO Undersea Research Centre (NURC), and the Centro Interdisciplinare di Bioacustica e Ricerche Ambientali (Interdisciplinary Center for Bioacoustics and Environmental Research; CIBRA) array from the University of Pavia. All arrays were towed simultaneously behind the ship that moved at 4 km along the survey transects.

2.1 FWG Array

The hydrophone array from Bundeswehr Technical Centre (WTD 71)-FWG was planned and specified by the FWG and built by Seiche Ltd. using those specifications. It is a modular, scalable system for detection, transmission, and recording of acoustic data. The acoustic antenna of the system consisted of up to three 10-m-long sections, each including five hydrophones and temperature and pressure sensors. During this research cruise, only two sections were used, connected by a data cable 200 m long (Knoll et al. 2011). Due to triangulation, the position of acoustic sources could be estimated. The depth of the towed underwater section could be varied. The usual towing depth was between the surface and 250 m. The towing depth was regulated by the 300-m-long variable cable connected to the onboard devices and an optional weight. The system was deployed and recovered by a winch. During SIRENA 11, the array was towed at 20 m (section 1) and 50 m (section 2) water depth, and the total length behind the ship, including the cable, was ~440 m.

The upper signal frequency of the array was 200 kHz, which also allowed high-frequency recordings from dolphins and porpoises. The lower frequency limit could be varied by different high-pass filters (10 Hz, 100 Hz, 1 kHz, and 2 kHz). The whole chain of signal conditioning, including digitizing and converting the data for optical transmission by fiber optics, was an integrated part of the array. This approach allowed more flexibility for further development and add-ons.

During SIRENA 11, the incoming filtered data were sampled with 192 kHz and sent to the passive analysis software sonar-marine mammal acoustic detection (PASS-MMAD) system from Kaon Ltd. (Kaon 2009). PASS-MMAD is a special software for automatic detection and classification of marine mammal sounds. The software classifies sounds in three different frequency bands: low-frequency baleen whales (Mysticeti; 0–175 Hz); high-frequency baleen whales (175 Hz to 1.5 kHz), delphinid (Delphinidae)-like clicks and whistles, sperm whales (*Physeter macrocephalus*); and beaked whales (Ziphiidae; 1.5–96 kHz; Kaon 2009; Knoll et al. 2010; Ludwig et al. 2011).

Measurements were done using four hydrophone channels, two in the FWG array (one in each hydrophone section), one in CPAM, and one in CIBRA. All four incoming signals were displayed as spectrograms covering the frequency range of 0–96 kHz. In general, the system allows recording in ten channels simultaneously. Signals of special interest were recorded additionally as display graphics and sound files. Besides the automatic classification by PASS-MMAD, the recordings were supervised for 24 h by experienced observers for each hydrophone system. For the FWG recordings, the following parameters were registered: times of detection, channel, species (delphinids, sperm whale, beaked whale), probability of species type (1 = certain to 5 = unsure), sound type (click, buzz, whistle, other), quality of detection (signal-to-noise ratio [SNR]), simultaneous detection with another system (CPAM, CIBRA), and special remarks (e.g., ship noise).

2.2 CPAM Array

The CPAM was developed at the NURC for marine mammal detection. The system consisted of 6 hydrophones with 95 cm between them, positioned for a 3-dimensional localization of cetacean sounds (Hughes 2011). The system included an underwater towed body connected to three tubes equipped with sensors in a triangular configuration. The CPAM was towed ~300 m behind the ship at a water depth of ~100 m during SIRENA 2011. Data were transmitted via cable for onboard processing and recording. Incoming signals were observed and recorded continuously and classified by the observer following a semiautomatic procedure from the recording system that distinguished between beaked whales, sperm whales, and delphinid-like, human, and unknown sources. Displayed sounds were verified by the observers to be very similar to the FWG system. A special algorithm was used to detect beaked whales using the three-dimensional detection capabilities of that system (for details, see Hughes 2011; Zimmer 2012).

2.3 CIBRA Array

The CIBRA system consisted of an analog towed array that included two data channels, an adapted receiver, and connected work station (CIBRA 2012). The total length of the towed cable was 200 m and the usual towing speed was 4 km. Because of its low weight, it can be deployed and recovered by hand. This causes a shallow towing depth of 10–20 m. Therefore, during SIRENA 11, the CIBRA array was mostly in the water column above the thermocline. Two hydrophones were in the underwater section, spaced 8 m from each other. The bandwidth was 80 kHz, and data were transmitted by an onboard cable to the processing unit. A special software, SeaPro from CIBRA, University of Pavia, was used to record and display the acoustic data in real time. Using a sample rate of 192 kHz, WAV files up to 60 min long could be recorded. During the survey, the real-time data received by the CIBRA array were evaluated continuously by experienced observers, and detections were classified in the following categories: regular clicks, clicks and codas of sperm whales, delphinid clicks, high-frequency clicks > 8 kHz, buzzes, whistles > 8 kHz, whistles < 8 kHz, Cuvier's beaked whales (*Ziphius cavirostris*), ship noise, and sonar. Each observation got a quality index of the signals (0 = background to 3 = very loud) and a quantity index (0 = none to 3 = continuous). Detections of cetaceans were summarized every day in categories very similar to the other systems (delphinids, sperm whales, and beaked whales).

3 Performance of the PAM Systems

The quality of incoming signals was distinct between the PAM systems. The differences in registered acoustic detections made by the observers with the three different PAM systems can have various reasons. The position of the hydrophones within the water column is essential for good detection rates, taking into account the thermocline. The detection of signals coming from deeper water layers, e.g., from beaked whales, is easier with hydrophones towed at a greater water depth. This setup also has the advantage of lower background noise. The thermocline depth in the research area was estimated at ~20 m, and the formation of a sound channel was found to be between ~50 and 150 m (Knoll et al. 2011). Therefore, the towing depth of the CPAM array (~100 m) was best suitable for recording sounds from deeper waters. The FWG array, with one section above and one below the thermocline (see Section 2.1), combines receiving sounds from greater depth and from the surface layer.

The CIBRA array is best suitable for sounds coming from the surface layer. The CPAM array could register the most signals. If clicks of beaked whales and delphinids occur at the same time, the beaked whale detections can be masked due to the overlaying delphinid sounds close to the ship. Two types of interference of electronic noise were recognized as intermittent in the FWG array. Narrowband interference was caused by the energy supply and broadband interference was caused by data transmission via fiber optics. A 30-s snapshot of spectrograms (normalized), including dolphin clicks and whistles, recorded with the three systems at the same time during SIRENA 11, shows the differences between the signal inputs and possible disturbances (Fig. 79.1). The slight time shift between the spectrograms was caused by minor differences in data transmission from the arrays to the onboard processing units for each PAM system.

The CPAM system shows the clearest and strongest signals. The FWG array presents good signals at section 1 and the deeper section 2 includes more noise (Fig. 79.1). This confirms the assumption that most disturbances within the FWG array were caused by the data transmission itself (connectors, oil-filled hydrophone section, and tow cable). Constant disturbances were observed at ~6.5 kHz for both hydrophone sections. The CIBRA array was influenced by a relatively high level of background noise (e.g., waves) due to its shallow towing depth (Fig. 79.1).

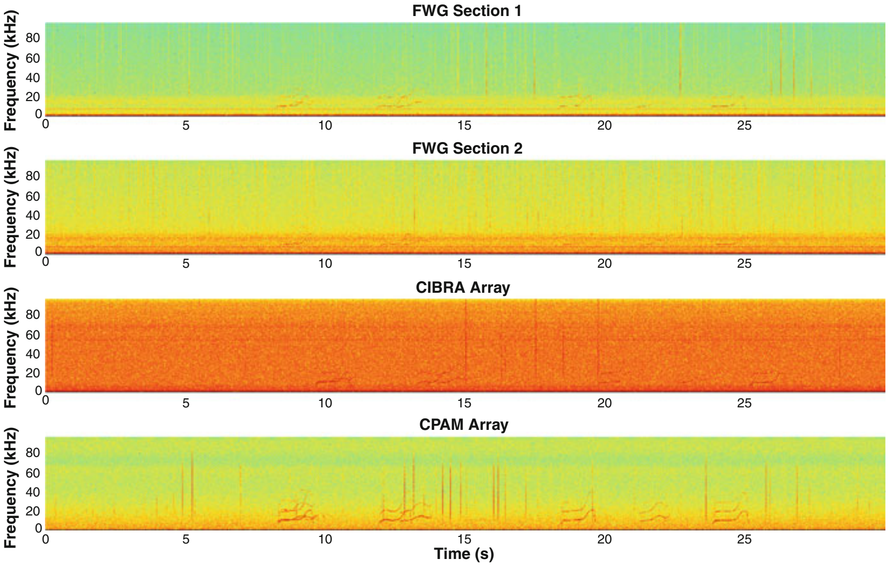

Fig. 79.1 Four snapshots of spectrograms (normalized) obtained with the different acoustic arrays (Research Department for Underwater Acoustics and Geophysics [FWG] sections 1 and 2, Centro Interdisciplinare di Bioacustica e Ricerche Ambientali [Interdisciplinary Center for Bioacoustics and Environmental Research; CIBRA], and compact passive acoustic monitoring [CPAM]) covering 30 s in a frequency range up to 96 kHz. Clicks and whistles of delphinids are shown

4 Acoustic Marine Mammal Detections

During phase 1 (July/August) and phase 2 (October) of the research cruise SIRENA 2011, delphinids, sperm whales, and some Cuvier's beaked whales were detected by the acoustic devices. The FWG hydrophone array was deployed on the line transect route for 167 h during phase 1, and operators detected dolphins for 62.4 h and sperm whales for 13 h. During phase 2, the total time of deployment was 157 h; operators registered dolphins for 78.7 h, sperm whales for 16.5 h, and Cuvier's beaked whales for 0.9 h. The results of the FWG array included detections from both hydrophone sections. In parallel to the acoustic survey, visual observation was conducted during daytime hours following line transect methods.

Overall, the number of acoustic detections was higher than that for visual observations; beaked whales were mainly encountered acoustically. Acoustic activity of the detected species groups was distinguished between day- (530-1800 universal time coordinated [UTC]) and nighttime hours (1800-0530 UTC). It has to be considered that because of the hydrographic measurements (current, temperature, depth) during 0400-530 UTC and 1700-1930 UTC, there was some off-effort time and the acoustic devices had to be recovered and redeployed immediately afterward on the last transect route position for complete coverage.

Delphinids, as striped dolphin (*Stenella coeruleoalba*) and short-beaked common dolphin (*Delphinus delphis*), detected by the FWG system and validated by its observers, showed a clear tendency for higher acoustic activity during nighttime hours (Fig. 79.2). No daily differences were observed for sperm whales. Detected Cuvier's beaked whale activity was higher during daytime hours. However, the relatively low

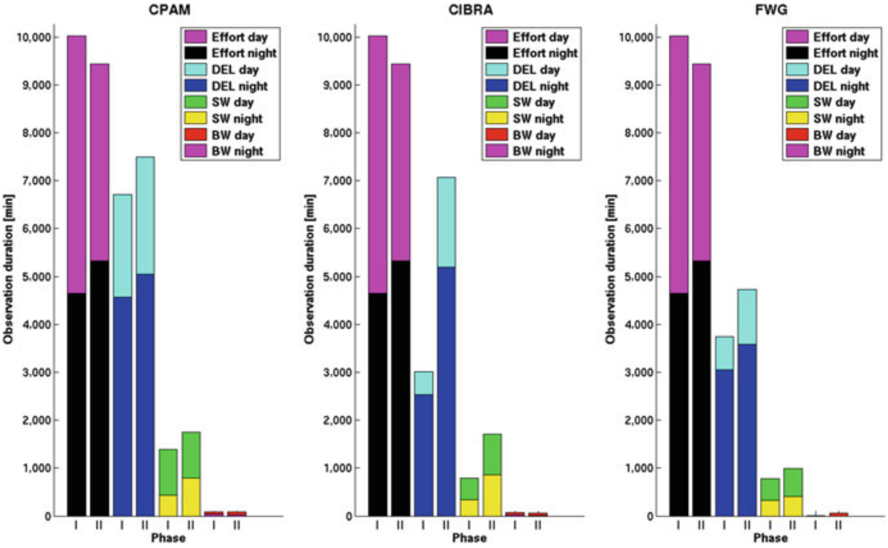

Fig. 79.2 Comparison of detected sounds for the species groups delphinids (DEL), sperm whale (SW), and beaked whale (BW) with the PAM systems CPAM, CIBRA, and FWG, divided into phases I and II of the research cruise SIRENA 11 and into daytime and nighttime detections

Table 79.1 Estimated SNR of the different PAM systems

PAM system	Estimated SNR (dB)
CPAM	19–23
CIBRA	~6
FWG section 1	10–18
FWG section 2	8–18

SNR signal-to-noise ratio, *PAM* passive acoustic monitoring, *CPAM* compact PAM, *CIBRA* Centro Interdisciplinare di Bioacustica e Ricerche Ambientali (Interdisciplinary Center for Bioacoustics and Environmental Research), *FWG* Research Department for Underwater Acoustics and Geophysics

number of detections doesn't allow a statistical verification. The positions of the beaked whale detections were distributed in water depth between ~1,000 and 2,600 m.

The acoustic observation patterns made by the FWG array were also being seen with the other systems. The comparison of the three PAM systems shows that CPAM recorded the most signals of each species category (Fig. 79.2).

CPAM and CIBRA also registered most signals of delphinids during the nighttime hours (FWG phase I = 81% and phase II = 76%; CPAM phase I = 75% and phase II = 67%; CIBRA phase I = 84% and phase II = 73%). Sperm whales didn't show significant differences between day- and nighttimes for each system (Fig. 79.2). Beaked whales were detected predominantly during daytime hours (CPAM phase I = 70% and phase II = 80%; CIBRA phase I = 69% and phase II = 93%; FWG = 100% for phases I and II; Fig. 79.2). Altogether the FWG array showed a good detection rate for delphinid and sperm whale sounds as confirmed by the reference CPAM.

The comparison of simultaneously detected events (±30 s) between the systems showed longest detection periods for the CPAM system. The FWG array had a false alarm rate of ~6% for delphinids and sperm whales compared with the CPAM array and captured ≥50% of the CPAM detections for these species groups. Especially during daytime hours, the detection ability of the CPAM array was obviously higher than for the other two systems.

To determine the suitability of the different PAM systems for use with an automatic classifier as presented in the Chapter 69 by Kreimeyer and Ludwig, the signals shown in Fig. 79.1 were applied to the classification algorithm. The results of the automatic classifier reflect the findings shown in Section 3. The classifier works best on the data supplied by the CPAM array where the best SNR is estimated (Table 79.1) and the sequence is correctly classified as delphinids. The low SNR from the CIBRA array caused some misclassifications among delphinids, seals, and baleen whales. The supplied signal of the FWG array (Table 79.1) allows a good classification of the clicks, whereas the classification performance is affected in the upper frequency bands by broadband noise.

5 Conclusions and Outlook

A good number of sounds from delphinids and sperm whales could be detected with the FWG array compared with the reference system CPAM. Also, beaked whale sounds could be observed, although interfering signals from dolphins close to the array were masking these weaker clicks coming from the deeper water layers. The CPAM, towed at the greatest depth of all devices, picked up the most beaked whale signatures. About 94% of the detections made by the FWG array were confirmed by detections with CPAM. Some narrowband and broadband interferences within the FWG data caused occasional detections to be missed. In general, the array performed as a robust and reliable system. Actually, the FWG array is being improved as a state-of-the-art detection tool, taking into account optimizations for detection and data transmission (Knoll et al. 2011; Ludwig et al. 2011). It is planned to use this as a standard tool for marine mammal research and risk mitigation within projects of the WTD 71.

The acoustic detection of delphinids showing high nighttime activity was also observed previously in the Ligurian Sea (Gordon et al. 2000). Sperm whales didn't show daily differences, and beaked whales were mainly found during the daytime, exclusively in deeper water (≥1,000 m). These observations were very similar during both phases (July/August and October) of SIRENA 11.

In general, the FWG array showed a good performance for the use with an automatic classifier (see Chapter 69 by Kreimeyer and Ludwig). For future use, the possibility of beam forming will be implemented to improve the detection and classification abilities of the array. On the automatic classifier's side, models to exclude sources of noise (e.g., ship noise) can be added.

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Chapter 80
Cardiorespiratory Responses to Acoustic Noise in Belugas

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Abstract To date, most research on the adverse effects of anthropogenic noise on marine mammals has focused on auditory and behavioral responses. Other responses have received little attention and are often ignored. In this study, the effect of acoustic noise on heart rate was examined in captive belugas. The data suggest that (1) heart rate can be used as a measure of physiological response (including stress) to noise in belugas and other cetaceans, (2) cardiac response is influenced by parameters of noise and adaptation to repeated exposure, and (3) cetacean calves are more vulnerable to the adverse effect of noise than adults.

Keywords Noise • Beluga • Heart rate • Breathing • Stress

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1 Introduction

Acoustic noise is one of the major anthropogenic impacts on marine mammal life. To date, the majority of studies have examined the effects of loud noise on hearing (e.g., Nachtigall et al. 2003) and behavioral response (e.g., Southall et al. 2007). Other effects of acoustic noise on marine mammals have not been well examined and are often ignored. However, the physiological nonauditory impacts of noise can be equally disturbing and devastating, particularly if the noise in unavoidable. They may include hypertension, tachycardia, myocardial infarction, and stress as described in humans (e.g., Seidman and Standring 2010; Sørensen et al. 2012).

The most reliable tool to evaluate animal discomfort or stress is the measurement of activity of the sympathetic system and hypothalamus-pituitary-adrenal axes such as catecholamines, ACTH, and cortisol (e.g., Mormède et al. 2007; Merlot et al. 2011). However, heart and breathing rates are also used to evaluate the response and state of the autonomic nervous system of humans and terrestrial mammals under the conditions of anxiety and stress (Fallani et al. 2007; Aschwanden et al. 2008) as well as when exposed to a fatiguing acoustic noise (Holand et al. 1999). At the same time, no such investigations have been conducted in cetaceans except for a brief study in a single bottlenose dolphin. Miksis et al. (2001) reported that the heart rate (HR) in this individual accelerated on when presented with the audio recording of whistling of other animals. The objectives of this study were to investigate the effect of loud acoustic noise on the HR and breathing pattern in belugas.

2 Methods

The study was conducted on three juvenile belugas housed at the Utrish Marine Station of the Russian Academy of Science (Black Sea, Novorossiysk, Russia). During the experiments, the belugas were placed on a stretcher and transferred to a bath with seawater (4×0.8×0.8 m). The animals were exposed to an octave-band acoustic noise (frequency: 9.5–13, 19–27, 27–38, 54–78, and 78–108 kHz; intensity: 140–175 dB; duration: 1–100 min). Electrocardiograms (ECGs) were recorded using two disk electrodes embedded in suction cups and an amplifier and were then digitized. Instantaneous HR was calculated by measuring the R–R intervals on ECG recordings. The duration of breathing pauses (BPs) was calculated as the time between two consecutive blowhole openings accompanied by audible respiratory acts.

Acoustic noises were presented 1–6 times/experiment and each lasted 2–4 h. A total of 16–21 experiments were conducted on belugas. Over the course of the study, each beluga was exposed to different acoustic noises more than 60 times. Two series of experiments were conducted in Beluga 1 two months after capture when the animal was ~1 year old and then 1 year later when the animal was ~2 year old. Belugas 2 and 3 were studied when they were ~2 and 3–4 year old, respectively. By the time the experiments were started, Belugas 2 and 3 had been living in captivity for ~1 year.

3 Results

3.1 Breathing-Related Cardiac Arrhythmia

The HR of the beluga calmly lying in the stretcher was characterized by expressed respiratory sinus arrhythmia, i.e., periods of bradycardia (instantaneous HR decreased to as low as 20 beats/min), which accounted for the phase of breath holding or apneas (respiration pauses longer than 60 s) alternating with periods of accelerated HR (up to 85 beats/min) concurrent with a series of respirations or eupneas (2–10 over 30-s intervals). Histograms of distribution of instantaneous HR values in belugas had two distinct peaks, with maxima at 30–40 beats/min, corresponding to the period of breath holding, and 60–80 beats/min, corresponding to the period of breathing (Fig. 80.1).

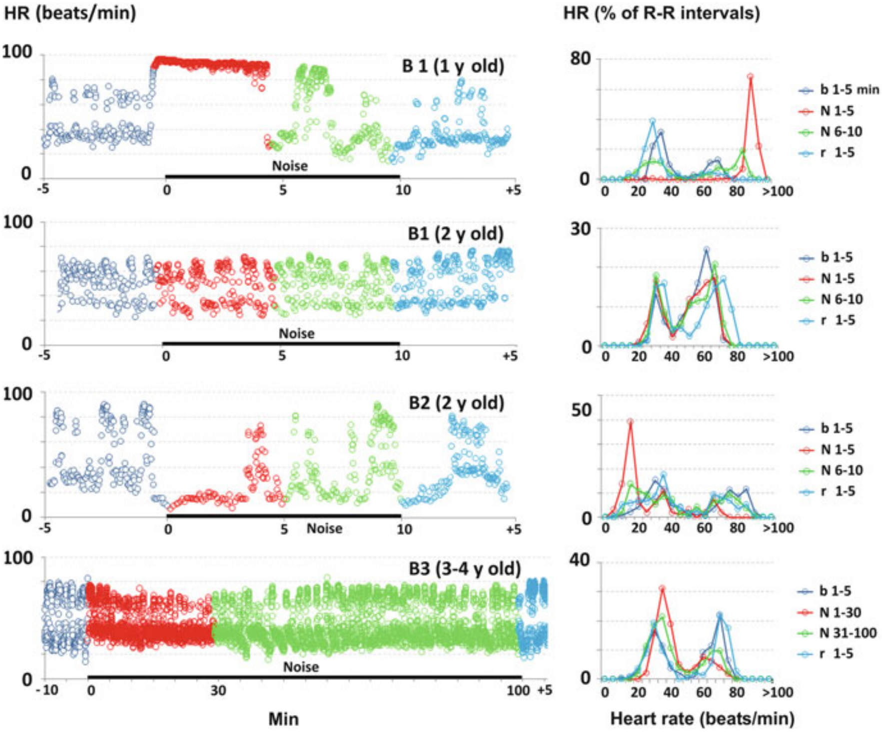

Fig. 80.1 *Left*: Instantaneous heart rate (HR) in belugas (B1 to B3) during presentation of acoustic noise. *Right*: Histograms of distribution of instantaneous HR for the corresponding diagrams in belugas during baseline (b), at 10 and 100 min of noise (N), and after the noise presentation (recovery [r]). Noise parameters are 27–38 kHz, 150 dB for B1 (1 year old) and B2; 19–27 kHz, 165 dB for B1 (2 year old); and 27–38 kHz, 165 dB for B3

3.2 Response to the Noise Onset

In Beluga 1, in the first series of experiments, acoustic noise evoked a HR acceleration, manifesting pronounced tachycardia (Fig. 80.1). The instantaneous HR reached the maximum value during the first seconds after the noise onset, up to 100 beats/min, 15 beats/min greater than the baseline value. The average instantaneous HR increased up to 210% of the baseline level for the first minute of the exposure. The typical 2-peak or bimodal distribution of instantaneous HR values became monomodal, with 1 pronounced peak with a maximum at 95 beats/min as shown by histograms. The pattern of breathing in Beluga 1 changed concurrently with the HR acceleration; the proportion of short BPs (<20 s) increased and the ratio of longer BPs (>20 s) decreased (Fig. 80.2).

In the second series (at the age of 2 years, after 1 year live in captivity), the response to the noise in Beluga 1 was less pronounced or not detectable (depending on the noise frequency and intensity; Figs. 80.1 and 80.2).

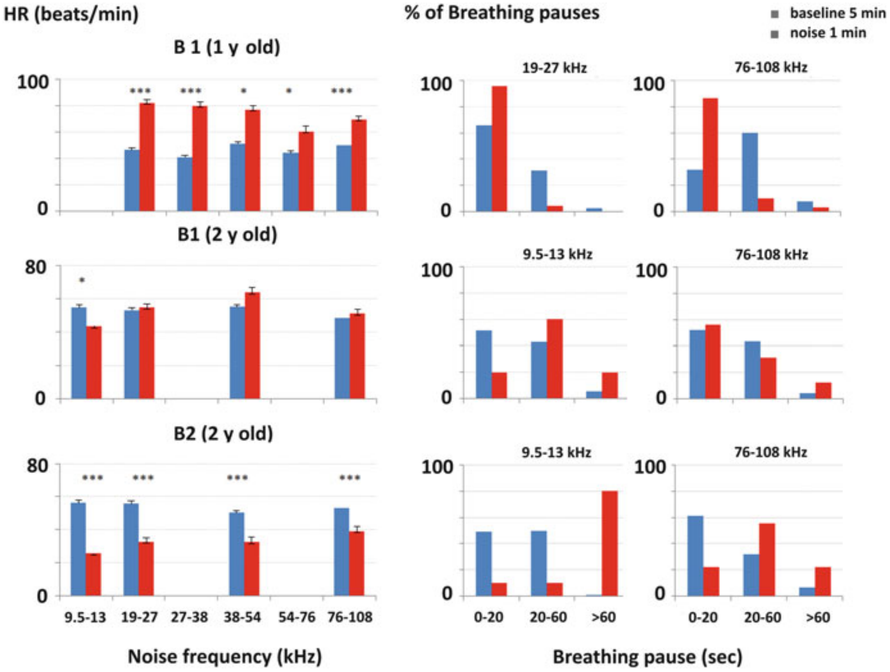

Fig. 80.2 HR (*left*) and patterns of breathing (*middle* and *right*) in belugas before and during presentation of 1-min acoustic noise. Values are means ± SE of HR and breathing pauses during baseline (5 min before the noise presentation; *blue*) and the first minute of exposure to noise (*red*). The breathing pauses are divided into three categories: short (<20 s), medium (20–60 s), and long (>60 s). The intensity of noise is 150 dB for B1 (1 year old); 160 dB for B1 (2 year old); and 160 dB for B2. Significant difference in HR between baseline and noise exposure: **P*<0.05, ****P*<0.001

In Beluga 2, the response to acoustic noise was opposite to that of Beluga 1; the instantaneous HR decreased (as low as 5 beats/min) and remained below 20 beats/min for at least 4 min of the exposure (Fig. 80.1). The histogram of instantaneous HR had a major peak, with a maximum at 15 beats/min. The changes of breathing pattern in response to the noise onset in Beluga 2 were also opposite to that of Beluga 1; the proportion of short BPs decreased while the proportion of long BPs increased (Fig. 80.2).

In Beluga 3, no pronounced response to acoustic noise onset was detected as measured by instantaneous HR and BP durations (Fig. 80.1).

3.3 Intensity and Frequency of Acoustic Noise and Cardiac Response

In all belugas, the expression and duration of the response to noise depended on both the noise intensity and the frequency (Fig. 80.2). In Beluga 1, a 150-dB acoustic noise evoked a sharp HR acceleration at all noise frequencies (*t*-test, $P<0.03$ for all frequency ranges). The magnitude of acceleration of HR at frequencies of 19–27 and 27–38 kHz was much greater than at frequencies of 54–78 and 78–108 kHz (paired comparison, $P<0.05$; after ANOVA, $P=0.02$; $F_{4.35}=3.21$). The HR acceleration in response to a 1-min 140-dB noise (on average 127% greater than the baseline values; frequencies of 19–27 and 27–38 kHz) was smaller compared with 150- (186%) and 160-dB (160%) noise (ANOVA, $F_{2.28}=5.419$, $P=0.01$; paired comparison, $P<0.02$). In the second series (age of 2 years), the instantaneous HR increased during the first minute of the noise exposure for all frequencies tested (9.5–108 kHz). However, this increase was significant only for the lowest frequency of 9.5–13 kHz (165 dB; Fig. 80.2).

In Beluga 2, a 1-min 165-dB noise caused a deceleration of HR at all noise frequencies (*t*-test, $P<0.001$; Fig. 80.2). During the first 1 min of noise exposure, the average HR decreased to 20% of the baseline value. The magnitude of bradycardia was the highest at the noise frequency of 9.5–13 kHz (the average HR was 45% lower than the baseline values) and progressively decreased when the frequency increased to 78–108 kHz (74%). However, the effect of the noise frequency on the HR response in Beluga 2 was not significant ($P>0.05$). At noise intensities of 145–165 dB, the degree of bradycardia in Beluga 2 was similar ($P>0.05$; tested for the frequency of 38–54 kHz).

3.4 Response to the Long-Lasting Noise

In all belugas, the HR changes caused by an acoustic noise were not limited to the first minute of the presentation (Fig. 80.1). Thus, in Beluga 1 for the noise frequency of 19–27 kHz, the evoked tachycardia lasted for a minimum of 4 min, so the average 1-min HR significantly exceeded the baseline values during this time (paired comparison, $P < 0.05$; after ANOVA, $P < 0.001$, $F_{3.27} = 39.41$). For higher frequencies, the increase of HR over the control values was significant only for the first minute of noise exposure (paired comparison, $P < 0.05$ for all frequencies). When the noise continued for more than 5 min, tachycardia in Beluga 1 was often replaced by bradycardia concurrent with apnea and those periods were longer than during the baseline. The distribution of instantaneous HR values became bimodal at that time as during the baseline. The instantaneous HR values as well as the breathing parameters returned to the normal values when the noise had been canceled (Fig. 80.1).

In Beluga 2, the average HR during the first 3 min of exposure was significantly lower than the average baseline HR ($P < 0.05$ for the first and third minutes; frequencies of 9.5–13, 19–27, and 38–54 kHz). The pattern of instantaneous HR in this beluga often returned to the baseline value before the noise had been canceled. As shown in Fig. 80.1, starting from the sixth minute of a 10-min noise, the instantaneous HR was similar to that during the baseline.

The effect of prolonged exposure to acoustic noise (30–100 min) on HR and breathing rate was examined in Beluga 3. In most cases, the onset of noise did not cause any significant changes in the HR in this animal. However, while the noise continued the dynamic range of the respiratory sinus arrhythmia decreased (20–80 beats/min during baseline and 30–60 beats/min during noise exposure). As shown in Fig. 80.1, the described changes became apparent starting from the fifth minute of the exposure and lasted for at least 30 min after the noise had started. After that, the HR returned to the baseline pattern while the acoustic noise continued for additional 70 min.

4 Discussion

Several types of cardiac response to acoustic noise were displayed by belugas during this study. The tachycardia and bradycardia recorded in Belugas 1 and 2 were similar to the physiological reactions to startling described in different animal species. Acceleration of HR in Beluga 1 (a calf aged ~1 year old captured just 2 months before the study) in response to noise is the first component of the "acoustic startle response" that has been studied in detail in humans and terrestrial mammals (Vila et al. 2007). When familiar conditions change, HR may increase up to 60% compared with the normal values. This acceleration is considered the cardiovascular component of the stress reaction and is accompanied by activation of the sympathetic nervous system, indicator of animal defense reaction and level of stress (Herd 1991; Merlot et al. 2011). Prolonged tachycardia, in turn, may cause additional cardiovascular and other medical problems (Seidman and Standring 2010; Sørensen et al. 2012). Deceleration of HR recorded in Beluga 2 in response to noise resembles a startle response recorded on presentation of strong unexpected stimuli. For instance, a similar reaction was observed in manatees in response to approaching humans and it was interpreted as a "cardiac response to a stressful impact" (Galanzev 1988). At the same time, periodic HR accelerations and decelerations are normal for all marine mammals. They constitute one of the components of the "dive response."

It should be emphasized that in Beluga 2 the temporal and frequency ranges of the HR were similar during the normal respiratory cycle and in response to acoustic noise. However, the tachycardiac response caused by acoustic noise in Beluga 1 was not typical for the “normal” condition and appears to be a more pronounced reaction to fatiguing noise.

The data collected in Beluga 3 indicate that a short latency (immediate) cardiac response to acoustic noise may not be present at the noise onset. At the same time, the response can develop later while the noise continues affecting the parameters of HR and breathing for a period of 30 min or even longer if the animal cannot avoid the noise exposure. Even if the pattern of HR during this period deviated less from the baseline value (e.g., compared with a 200% acceleration in Beluga 1), the duration of these changes appears to be a more crucial factor. The impacts of such long-lasting changes of the normal pattern of HR for the animal’s state and health have never been evaluated and remain unclear.

In all belugas, the pattern of breathing changed concurrently with the HR; the proportion of short BP increased during tachycardia and the ratio of longer BP increased during bradycardia.

An interesting finding is that the cardiac response to loud noise was maximally expressed in a 1 year-old beluga calf shortly after it had been captured and placed in captivity with no evidence of habituation to repeated presentations at that time. However, the response was attenuated in 1 year when the animal was retested, suggesting that several factors such as the age, state, health, and prior experience of the animal with the sounds are responsible for the magnitude of the cardiac response.

It was shown that presentation of a long (30–50 min) 4–11 kHz acoustic noise to a bottlenose dolphin did not result in a temporary threshold shift (TTS) at an intensity of 171 dB. However, a clear TTS was obtained at an intensity of 179 dB (Nachtigall et al. 2003). In a beluga, a significant TTS was observed at noise intensities of 150 and 160 dB but not at 140 dB (Popov et al. 2011). Our data indicate that severe tachycardia may develop in belugas at lower noise intensities (as low as 140 dB). At higher intensities (150–165 dB), the HR reached a twofold increase over the baseline values and lasted at least 5 min. The intensity and duration of noise presented to the belugas in our study was lower than the levels of anthropogenic noise marine mammals may be exposed to in the ocean (Southall et al. 2007), suggesting that the cardiac response to the acoustic noise in the wild belugas may be even more pronounced. At the same time in the ocean, free-moving cetaceans are usually able to minimize the adverse effects of loud noise by moving away from the source of sounds. However, under the conditions of the current study, the belugas were restrained, which might cause a more pronounced response to the noise.

To conclude, HR may serve as a criterion of physiological response to fatiguing acoustic noises, including anthropogenic, in belugas and, most likely, in other cetaceans. The breathing pattern appeared to be a less informative parameter to measure physiological response to acoustic noise in belugas because it can be voluntary controlled. Additional information on the animal state during the exposure to loud noise may be gathered via blood biochemistry. Repeated exposure to acoustic noise may have both immediate and delayed impacts on marine mammals’ health.

For instance, it may cause serious cardiovascular problems and diseases as described in humans (e.g., Sørensen et al. 2012). Such studies have not yet been conducted in cetaceans. The data collected in this study also suggest that cetacean calves may be more vulnerable to the adverse effect of noise than adult animals.

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Chapter 81
Acoustic Communication in Fishes and Potential Effects of Noise

David A. Mann

Abstract Many soniferous fishes such as cods and groupers are commercially important. Sounds are produced during courtship and spawning, and there is the potential for aquatic noise to interfere with critical behaviors and affect populations. There are few data on the response of wild populations of sound-producing fishes to acoustic noise. New motion and sound exposure fish tags could be used to assess the behavioral responses of large numbers of fish to noise exposure. Many factors, such as fishing mortality and environmental variability in prey supply, could also affect populations and potentially interact with the behavioral responses to noise.

Keywords Toadfish • Sciaenidae • Grouper • Passive acoustics • Glider

1 Introduction

Although the importance of acoustic communication in marine mammals has long been appreciated, there has been a lag in the study of acoustic communication in fishes. This paper reviews acoustic communication with a focus on the aspects of communication as they relate to potential impacts from noise in three groups of fishes that are among the better studied soniferous fishes: toadfish (Batrachoididae), croakers and drums (Sciaenidae), and groupers (Epinephelidae). The paper closes with a call for a large-scale multi-investigator effort to catalog fish sounds and the development of technology to study the impacts of noise on communication and reproduction.

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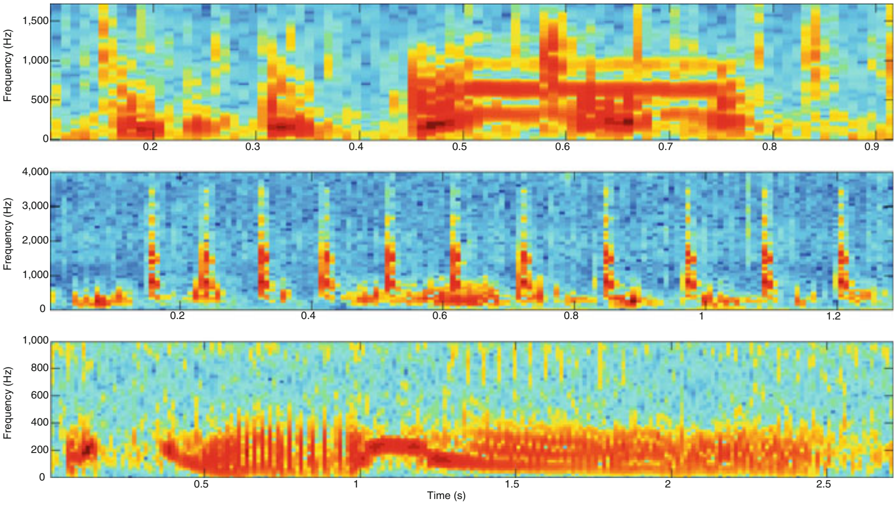

Fig. 81.1 Spectrograms of sounds from gulf toadfish (*top*), silver perch (*middle*), and red hind grouper (*bottom*)

1.1 Toadfish

Toadfish have been used as a model to study acoustic communication at the neural level (e.g., Sisneros and Bass 2005) as well as in field studies of behavior (e.g., Thorson and Fine 2002). There are about 80 species of toadfish, yet the sounds of only a handful have been described (e.g., Tavolga 1958; Amorim et al. 2011). Toadfish produce sounds by contraction of the sonic muscles that are intrinsic to the swim bladder. The rate of muscle contraction is mirrored in the fundamental frequency of the sounds, which ranges from 50 to 400 Hz (Fig. 81.1). There are species-specific differences in the duration and timing of these sounds. In toadfish, males establish a nesting area and vocalize to attract females who lay adhesive eggs in the male's nest. Toadfish communication is likely short range (<10 m) due to the source level of the sounds (126 dB re 1 μPa; Barimo and Fine 1998) and the relatively poor hearing sensitivity of toadfish (Fish and Offutt 1971). Toadfish have been demonstrated to interact with neighbors vocally. Thorson and Fine (2002) showed that the gulf male toadfish will produce a thumping sound, termed tagging, simultaneously with a neighbor's boat whistle.

1.2 Croakers and Drums

There are about 275 species of croakers and drums, which are found coastally in the tropics and subtropics. Although most species produce sounds, there are some species like whiting that lack swim bladder musculature. Croakers and drums typically have sonic muscles that attach between the bone and the swim bladder.

Sounds are typically a series of pulses (e.g., Fig. 81.1), but there are some species where the pulses are rapid and appear tonal in nature (e.g., black drum; Locascio and Mann 2011). Sound production has been described in ~15 species, which leaves the majority unknown. Some croakers will produce sounds in a chorus when many individuals in the same area produce sound simultaneously (Locascio and Mann 2008). In these situations, it can be difficult to discern the call of an individual. In estuarine areas in Florida in the summer, the low-frequency noise floor is often dominated by sound production by croakers and drums, which can be so loud as to be heard above the water. Croakers and drums have a wide diversity of swim bladder structure, which relates to a wide diversity in hearing sensitivity (Ramcharitar et al. 2006). The range of communication is not known. It has been estimated to be 33–108 m for the black drum based on the source level (165 dB re 1 µPa) and audiogram measurements (Locascio and Mann 2011). Even in this very loud species, the detection range was background noise limited. In species that chorus, the detection range for the chorus could be larger than for an individual calling.

1.3 Groupers

Groupers are found in the tropics and subtropics and are a common local food fish. Sound production has been most commonly associated with the family Epinephelidae. There are 159 species of epinephelids, and sounds have been identified from 5 species (e.g., Mann et al. 2010; Nelson et al. 2011; Schärer et al. 2012). Several species, such as red hind and red grouper, produce a relatively complicated sound for a fish, consisting of an introductory set of pulses followed by a pulse train with increasing or decreasing pulse rates (Fig. 81.1).

The sound production mechanism is not well understood; sound production appears to be mediated by muscles on the vertebral column in Nassau grouper (Hazlett and Winn 1962). There are no direct measurements of source level for any grouper sound, although estimates based on nearby recordings suggest it is ~130–140 dB re 1 µPa for red grouper, with a peak frequency of ~180 Hz (Nelson et al. 2011). Video recordings of red grouper and red hind suggest that acoustic communication is relatively short range (<100 m), and signal-to-noise ratios of recordings also suggest detectability to be in the range of 100 m.

2 Potential Effects of Noise

In all of these examples, acoustic communication is an important aspect of reproduction. Acoustic communication ranges are likely relatively short for all species (<100 m). Still, for croakers, drums, and groupers in coastal areas, the background noise rather than hearing sensitivity is most often the limiting factor for communication range. Because toadfish might be mainly sensitive to particle motion, it is possible that their hearing sensitivity limits the communication range. One might expect these relatively short communication ranges to hold for most fish species.

The exceptions might be for chorusing fishes and fishes who live in environments with a lower noise floor (e.g. deep sea and freshwater lakes).

The most likely potential negative impact of noise on fish communication is to reduce communication ranges and potentially disrupt spawning. Many of these species are producing sounds in murky water or at night, and thus acoustic communication may be an important means of locating potential mates. One would expect the largest potential impact to come from chronic, low-frequency (<1,000 Hz), high-level sound sources that raise the background noise floor, such as in harbors where there is consistent engine noise.

Passive acoustic recording could be used to measure the disturbance to fishes. My laboratory has recorded large changes in sciaenid sound production in response to red tide events as well as to hypoxia. In New Jersey, large changes in sound production accompanied large changes in water temperature due to upwelling (Mann and Grothues 2009). Similarly, one could study the impacts of noise exposure from seismic air guns on fish behavior with passive acoustic monitoring. This should be readily achievable by piggybacking on existing seismic surveys.

3 Need for Library of Fish Sounds

Recent recordings made from an underwater glider in the Gulf of Mexico showed the presence of several common sounds that were likely produced by fishes (Wall et al. 2012). This glider track was 135 km in length and took place over a 1-week time period. Indeed, the majority of the sounds recorded came from unknown sources. Of the three groups described in Sections 1.2 and 1.3, recordings have been made in <5% of the species. This demonstrates the comparative ignorance about the sources of sound in marine environments compared with those in terrestrial environments. This ignorance limits the use of passive acoustics to study the effects of noise exposure on fish behavior because in most cases the species being recorded will be unidentified.

A concerted effort is needed to develop a library of fish sounds. This will allow us to learn about the ecology of fishes and also study the impacts of noise using passive acoustic techniques. Many of the sounds produced by fishes take place during courtship and reproduction, which can be difficult to replicate in the laboratory where it can be difficult to impossible to breed fish. For example, the sound produced most commonly by red hind in the field during territorial behavior was nothing like the single pulses recorded as fish were manipulated in captivity (Fish and Mowbray 1970; Mann et al. 2010). For species like the red hind, which live on relatively shallow coral reefs, it was possible to use video cameras with hydrophones to identify sounds. In other environments, where the visibility is poor or the water too deep, video cameras are impractical.

A fish acoustic library will likely contain thousands of species. Thus, new techniques such as implanted tags that record sound production are needed to record sounds directly from fishes.

4 Fish Behavioral Response Tags

Acoustic tags for cetaceans have been very successful in studying natural behavior and sound production during feeding (e.g., Johnson and Tyack 2003). These tags are too large to use directly with fishes. I propose a new type of tag using an accelerometer sampled at a high rate to record fish sound production. An accelerometer may be superior to using a piezoceramic hydrophone to record sound production from an implanted fish because it is directional and would detect motion and not sound pressure. Thus, it will have a lower noise floor from external sound sources such as other fish sounds and boat noise. Current digital accelerometers support sample rates up to 1,200 Hz, which is adequate for covering the typical bandwidth of fish sound production. These tags could be digital storage tags using onboard memory but then they would have to be recovered. Another possibility is to integrate these tags with an acoustic transmitter so that the recorded signals could be transmitted to a receiver that is easy to recover. This tag design could be extended to study behavioral responses to noise exposure by adding a hydrophone to record noise exposure and a magnetometer and depth sensor to record swimming behavior.

5 Challenges

Looking forward, even with the necessary technology and knowledge, it will be a major challenge to disentangle the effects of noise exposure from environmental variability and fishing mortality. In 2008, the Florida west coast commercial red grouper catch was over 5.6 million pounds and the recreational catch was estimated at over 1,30,000 pounds (Southeast Data, Assessment, and Review 2009; National Marine Fisheries Service 2012). Even though this catch is a fraction of that of other fisheries, it is likely going to be nearly impossible to directly ascribe a specific population impact of noise exposure by counting fish. What can be measured? One can envision controlled studies where short-term reproductive output and behavioral correlates of reproduction, such as sound production and fish movement, are measured in the absence and presence of noise exposure. Although it is attractive (and easier) to do these studies in areas with no fishing, it is possible there will be interactive effects from noise exposure coupled with fishing pressure.

By answering this short-term question of whether there is an impact on behavior and reproduction, we can begin to estimate the risk associated with noise exposure to populations. If there is little or no disruption of behavior and reproductive output, then it is unlikely that noise will be an important risk factor, especially in comparison to the effects of fishing. However, if there are large disruptions to behavior, such as movement out of an area or cessation of sound production and spawning, then the risk of noise exposure will be higher and the level of risk will be tied to the spatial and temporal extent of noise exposure in relation to the spatial and temporal extent of spawning.

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Chapter 82
Evaluation of Three Sensor Types for Particle Motion Measurement

Bruce Martin, David G. Zeddies, Briand Gaudet, and Joel Richard

Abstract All fish sense acoustic particle motion; some species also sense pressure. Concern over the effects of anthropogenic sounds is increasing the need to monitor acoustic particle motion. Particle motion can be measured directly using vector sensors or calculated from pressure gradients. This article compares three devices that measure particle motion: a three-axis accelerometer, a three-axis velocity sensor, and two 4-element hydrophone arrays. A series of sounds (constant-wave tones, white noise, and Ricker wavelets) were played from a fixed-position projector. The particle motion of sounds from imploding light bulbs was also measured.

Keywords Accelerometer • Particle velocity • Fish hearing

1 Introduction

Sound pressure is what terrestrial ears sense and is the component of sound measured by a microphone or hydrophone. Sound pressure measures fluctuations in the density of the medium due to the presence of sound. Particle motion is a less familiar concept. It refers to the movement of the particles that make up the media when sound is present. This movement is described in terms of particle displacement, velocity, or acceleration. Pressure and particle motion are both valid descriptions of a passing sound wave, but an important distinction between the two is that pressure is a scalar measure (having only magnitude), whereas particle motion is a vector measure (having magnitude and direction).

All fish directly sense the particle motion component of sound (Fay 1984), but relatively few fish sense the pressure component (Popper and Fay 1999). The ears of all fish consist of otolith- (or otoconia-) containing end organs that function as

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inertial accelerometers. The body of the fish moves with the same displacement, direction, and phase as the water around it because fish tissue has about the same acoustic properties as water. Otoliths and otoconia are denser than water and in the presence of sound, they move with a smaller amplitude and lag in phase relative to the body of the fish, which causes relative motion between the otolith and the sensory hair cells. Some fish have additional morphological adaptations that allow them to perceive pressure (e.g., Popper and Fay 1999). In these fish, gas-filled bubbles near the ear (and the swim bladder) or mechanical connections between the swim bladder and the ear (Weberian ossicles) convey sound pressure from the water to the ear when the bubble deforms with pressure.

Due to concern over the possible negative effects of increasing anthropogenic sound on fish (McCauley et al. 2003; Popper and Hastings 2009; Slabbekoorn et al. 2010), many countries now require impact assessments for marine sound-producing activities. Although the relevant exposure metric for most fish is particle motion, there is little regulatory guidance with respect to particle motion, and few particle motion measurements have been collected in conditions typically encountered in monitoring situations. The paucity of data is, in part, due to a lack of robust recording methods and a lack of experience recording particle motion. In this study, we compare three approaches to particle motion measurement: two sensor types that measure particle motion directly (a three-axis microelectromechanical system [MEMS] accelerometer and a three-axis velocity sensor) and four-element hydrophone arrays that measure the pressure gradient, from which we calculated particle acceleration. Testing was conducted at sea in conditions that may be encountered in monitoring situations.

2 Review of Particle Motion and Acoustic Measurements

Acoustic energy is transmitted mechanically by compression and rarefaction of the supporting medium. The changes in density associated with the passing acoustic energy can be measured as the pressure changes using microphones in air or hydrophones under water.

With a change in density, there must also be movement of the particles making up the media. This particle motion can be sensed directly with vector detectors such as accelerometers or velocity sensors. Particle motion can also be calculated from pressure gradient measurements. Using Newton's laws of motion and the equations of classical mechanics, a wave equation can be derived to fully describe a sound wave (see, for example, Beranek 1993, Chapter 2). A simplified description relating sound pressure and particle motion is Euler's equation of motion (Eq. 82.1) for fluids that is closely related to Newton's second law, $F=ma$, for motion of point sources. Euler's equation states that a gradient in pressure (∇p) across a volume is equal to the density (ρ_o) of the medium times the change in particle velocity ($\frac{\partial u}{\partial t}$; i.e., particle acceleration)

$$-\nabla p = \rho_0 \frac{\partial u}{\partial t} \tag{82.1}$$

Therefore, particle acceleration can be found by computing the difference in pressure across a volume, which can be measured using hydrophones at two or more locations. Particle motion in three dimensions can be obtained from an array of four hydrophones, with one hydrophone at the origin and the other three along the *x*-, *y*-, and *z*-axes (e.g., MacGillivray and Racca 2006). Particle acceleration can be integrated with respect to time to obtain the particle velocity and integrated twice with respect to time to obtain the particle displacement. Particle motion is a vector description of sound, so it is noted that particle motion provides information on the direction of the source as well as its intensity.

Assuming that a sound wave is measured far from the source (far field) and that the intensity of the sound is low (i.e., the pressure and density are directly related by the adiabatic bulk modulus), then Euler's equation can be simplified to an expression that directly relates pressure and particle velocity (Eq. 82.2)

$$u = {}^{p}\!/_{\rho c} \tag{82.2}$$

where *u* is the particle velocity, *p* is the pressure, ρ is the density, and *c* is the speed of sound. Equation (82.2) can be rearranged to provide a metric to determine how well an estimate of particle velocity matches the far-field assumption (Eq. 82.3)

$$\rho c u - p = 0 \tag{82.3}$$

3 Methods: Sensors, Data Analysis, and Trial Description

3.1 Sensors

Two mooring frames were deployed. Each frame was equipped with an orthogonal array of four M8E-51-35 omnidirectional hydrophones (−164 dBV/μPa sensitivity; GeoSpectrum Technologies, Inc.) spaced 30 cm apart and one vector sensor. A negatively buoyant M20 velocity sensor (GeoSpectrum Technologies, Inc.) was mounted in one frame and a neutrally buoyant micro-electronic-mechanical system (MEMS; 356B18, PCB Piezotronics) was mounted in the second frame. The M20 sensor includes an integrated omnidirectional hydrophone, a digital roll-pitch-yaw compass sensor, and three-axes acoustic velocity outputs. The bandwidth (to –10 dB) of the velocity sensors is ~300–3,000 Hz, with a peak sensitivity at 1,000 Hz. The beam pattern of the *x*-, *y*-, and *z*-axes of the sensor provides nulls greater than −25 dB off-axis. The 3-axis MEMS accelerometer has a nearly flat frequency response from 1 to 3,000 Hz, a sensitivity of 1 V/G, and nulls greater than −13 dB off-axis. The MEMS accelerometer was mounted in a small PVC pressure vessel to make it neutrally buoyant and then suspended from a compliant mount (similar to that in Zeddies et al. 2012). A digital orientation logger was secured to each frame to measure the orientation of the omnidirectional hydrophone arrays and the MEMS accelerometer.

Acoustic data were sampled at 64 kilosamples per second (ksps) using autonomous multichannel acoustic recorders (AMARs; JASCO Applied Sciences). Each mounting frame had two AMARs, one for the four-element omnihydrophone arrays and one for the particle motion sensor. Each AMAR synchronously sampled all four channels of input data.

3.2 Sea Trial

The at-sea trial was performed in November 2012 in St. Margaret's Bay, Nova Scotia, Canada, in water depths of ~30 m. The two mounting frames were deployed ~10 m apart. A moored projector was located ~8 m from the mounting frame that contained the M20 velocity sensor and 20 m from the frame that contained the MEMS accelerometer. The projector had a bandwidth (to −20 dB) of 600–1,600 Hz, with a peak frequency of 950 Hz and a maximum output power of 180 dB. The projector broadcasted a repeating pattern of signals that included (1) stepped tones from 50 to 12,800 Hz. The tones were octave spaced and lasted 10 s. At each step, the signal was broadcasted at full amplitude and at −20 dB re full scale, totaling 200 s; (2) pink noise for 10 s at full scale and −20 dB re full scale, totaling 20 s; (3) swept frequency-modulated signals (10–6,800 Hz, 1 s), repeated ten times, at full scale and −20 dB re full scale, totaling 20 s; (4) Ricker wavelets at a different time scales and at full scale and −20 dB re full scale, totaling 240 s; and (5) 420 s off, totaling 900 s.

The trial lasted ~3 h, during which time the deployment vessel, the DCD Rocker, a lobster fishing boat with a 6-cylinder 210 HP engine, spent approximately half the duration idling away from the trial location and then conducted a number of drifts past the recorders with its engines idling. The drift track where the vessel passed the arrays at a horizontal range of ~10 m was analyzed. Because only the start and end points of the tracks were recorded, a detailed comparison of the true vessel locations to estimates from the sensors cannot be performed. The DCD Rocker also went to various locations around the recorders to drop light bulbs that imploded at depth and created a low-frequency impulsive sound signal.

3.3 Data Analysis

To assess sensor performance, three measurements were made: the signal-to-noise ratio (SNR), the ability to correctly resolve bearing to the source, and accuracy of the velocity measurement.

The SNR was calculated from the tonal signals. For this analysis, the SNR was defined as the average signal level in the 1/3-octave band containing the signal divided by the average of the 1/3-octave bands on either side of it. The reported values are the averages of ten measurements of the root-mean-square (rms) signal level in 1 s of data with 50% overlap and a Hamming window applied.

The bearing to the sound source for the M20 velocity sensor and the MEMS accelerometer were calculated by performing the following steps: (1) defining the time and frequency window of the signal of interest; (2) computing the rms signal level for each axis of the sensor in the selected time-frequency window; (3) cross-correlating the signal from each axis with the omnidirectional hydrophone to determine the relative phase of the signal; and (4) computing the four-quadrant inverse tangent (ATAN2) of the x- and y-axes to get the bearing and the inverse tangent (ATAN) of the $\sqrt{(x^2+y^2)}$ and z-axis to obtain the elevation.

The bearing and elevation to the sound source for the omnidirectional hydrophone array were calculated by performing following steps: (1) defining the time and frequency window of the signal of interest; (2) cross-correlating the time-frequency window for each of the x-, y-, and z-hydrophones with the hydrophone at the origin to obtain the relative time delay of arrivals (TDOAs); and (3) computing the ATAN2 of the x- and y-axes TDOAs to get the bearing and the ATAN of the $\sqrt{(x^2+y^2)}$ and z-axis to obtain the elevation.

The accuracy of the bearing estimates was visually assessed and determined to be either correct or incorrect for the static projector as well as for the broadband vessel noise while drifting past the sensors.

The accuracy of the velocity measurement was determined by comparing the velocity measurement with the far-field velocity estimated from the pressure measurement using Eq. (82.3). Equation (82.3) shows that, in the far field for a planar wave, pressure is equal to particle velocity times acoustic impedance or $\rho cu-p=0$. Therefore, the magnitude of particle velocity can be calculated from the pressure measurement. For the M20 sensor, pressure (p) was measured using its integrated hydrophone. For the omnidirectional hydrophone arrays and the MEMS accelerometer, the pressure on the omnidirectional sensor at the origin of the orthogonal arrays was used. The magnitude of the velocity (u) was computed as the rms value of each of the x–y–z components of the velocity, i.e., $\sqrt{(u_x{}^2+u_y{}^2+u_z{}^2)}$.

4 Results

Table 82.1 shows the relative SNRs for each of the sensor channels for the set of tones generated from 1,639 to 1,642 on 12 November 2012. For the frame with the M20 sensor, the M20 and the M8 hydrophones had similar SNRs. Visual inspection of the data using time-series and spectral displays confirmed that the M20 responded well to the tonal signals. The results from the MEMS mounting frame were poorer than expected. The signal levels on the M8 hydrophones were 12–19 dB below the levels of the M8 hydrophones at the M20 sensor. Decreased SNRs were expected because of the further distance to the source; however, the levels and SNRs on the MEMS accelerometer varied wildly from octave to octave. Visual inspection of the time-series and spectrogram data showed many frequency bands dominated by noise and rapid changes in total signal level (15–20 dB) over periods of 1 s (for comparison, the levels on the omnichannels varied from 3 to 6 dB over 1 s). Based on these results, no further analysis of the MEMS data was undertaken.

Table 82.1 Relative signal-to-noise ratios

	Relative SNR, dB			
Frequency, dB	M8 Array at MEMS Sensor	MEMS Sensor	M8 Array at M20 Sensor	M20 Sensor
200	24		38	45.5
400	31	24	45.5	47
800	46.5	45.5	51.5	50.5
1,600	51	46	55	57.5
3,200	52	29.5	61.5	61
6,400	41	46	57.5	

Signal-to-noise ratios (SNRs) of tones were generated from 1,639 to 1,642 on 12 November 2012 at each sensor. The SNR is the difference between the average root-mean-square sound pressure level in the 1/3-octave band containing the tone and the average of the 1/3-octave bands on either side of the tone. Values are averages of ten 1-s root-mean-square sound pressure levels with 50% overlap and a Hamming window applied. The microelectromechanical system (MEMS) sensor mounting frame was ~20 m from the source and the M20 sensor mounting frame was ~8 m from the source

Table 82.2 Localization and particle velocity results

	Quad M8 Array (MEMS Frame)	M20
Accurate localizations, projector	23/100	42/100
$\rho cu - p$, dB ± SD	−2.3 ± 6.7	−7.25 ± 9.0
Accurate localizations, drifting vessel	120/120	120/120
$\rho cu - p$, dB ± SD	1.5 ± 2.3	0.05 ± 0.6

Localization accuracy is based on a visual inspection of the bearing lines (e.g., Figs. 82.1 and 82.2) and a comparison to the known locations of the sources. For the projector, 100 localizations were performed over a 6-min window from 1,639 to 1,645 (Fig. 82.1). For the drifting vessel, 120 localizations were performed over a 10-min window from 1,735 to 1,745 (Fig. 82.2). ρ, Density; *c*, speed of sound; *u*, particle velocity; *p*, pressure

Table 82.2 contains the localization accuracy and particle velocity estimation results for localizing on the signals from the projector (Fig. 82.1) and a drifting vessel (Fig. 82.2). Both sensors showed poorer performance localizing the projector than the drifting vessel. The estimates of the particle velocity show a similar pattern.

5 Discussion

The variable noise levels measured with the MEMS accelerometer suggest that the method of mounting it in the air-filled pressure vessel, its neutral buoyancy, or its compliant mount were not designed properly. The MEMS sensor can provide bearings and acceleration data at frequencies down to 1 Hz, which is desirable. Therefore, work on this sensor will continue in laboratory and field settings. The poor bearing estimation performance of the M20 velocity sensor and the M8 hydrophone arrays with the projector was initially surprising. The bearing performance of the M20

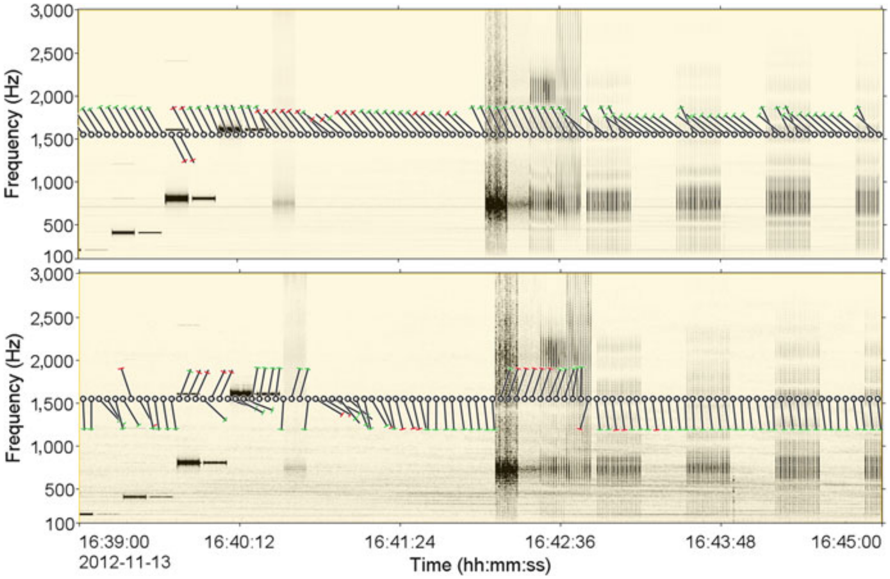

Fig. 82.1 M20 (*top*) and M8 (*bottom*) hydrophone array localizations on the projector transmissions from 1,639 to 1,645 on 12 November 2012. The *circle*-and-*line symbols* point in the estimated direction of the source. The *green* or *red hash marks* indicate the elevation, with *hash marks* at the *tip* of the pointer indicating horizontal and *hash marks* by the *circle* indicating vertical. *Red* indicates an elevation below the sensor and *green* indicates above the sensor. Actual bearing of the projector from the M20 hydrophone array was ~335 and from the M8 hydrophone array was ~010. The vessel was station keeping at ~300 to the M20 and ~290 to the M8 hydrophone array. Only *symbols* pointing at the projector were counted as being correct

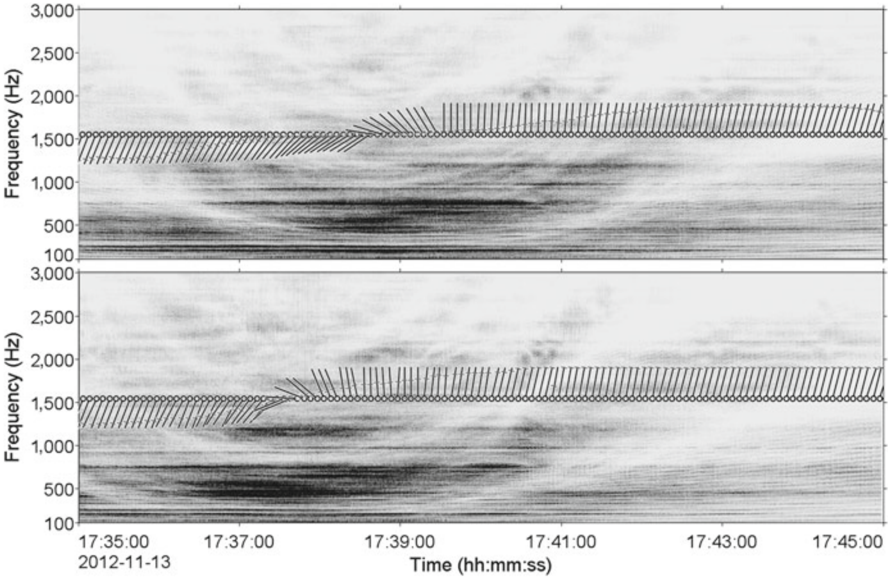

Fig. 82.2 M20 (*top*) and M8 (*bottom*) hydrophone array localizations on a drifting vessel from 1,735 to 1,745 on 12 November 2012. The vessel passed from nearly due south of the sensor to due north

sensor was good for signals that had high SNRs in the main band of the sensor (300–3,000 Hz) and for the broadband signals. The bearing performance of the M8 hydrophone array was only good for the pink noise and swept FM signals that had a high time-bandwidth product. A high time-bandwidth product is essential for the cross-correlation processing to output a precise TDOA for localization. The mean and variance of $\rho cu - p$ was particularly poor for the M20 sensor, likely because the sensor was located only 8 m from the source, which violates the plane wave (far-field assumption) that is required for $\rho cu - p = 0$ to be true.

The performance of the sensor for tracking the drifting vessel was good, both in terms of the number of accurate bearings and in $\rho cu - p$. The top of Fig. 82.2 (M20) shows two steps or gaps in the bearing estimates at bearings of ~260 and 350. These correspond to the nulls of the sensor response. If the nulls were deeper, the ATAN2 estimator would be better able to track the vessel bearing through the null. In some applications, the bearing to a source is determined by steering the null and minimizing the received signal on that channel. We expect that the MEMS sensor may have larger gaps in the bearing estimates because the transverse sensitivity (null depth) is only −13 dB.

Acknowledgments We acknowledge Craig Evans, Bob Trider, and the crew of DCD Rocker for trial support and JASCO's continuous support of our efforts to improve our acoustic measurement capability.

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Chapter 83
Regional Variations and Trends in Ambient Noise: Examples from Australian Waters

Robert D. McCauley, Douglas H. Cato, and Alec J. Duncan

Abstract Studies of ambient noise south of Australia show higher levels at low frequencies in the deep water off the continental shelf compared with locations on the shelf. The difference arises because of differences in transmission loss. Marine animals would experience significantly different noise levels and directionality in the two regions and while crossing the boundary, provide positional information. Opportunities for long-range, low-frequency communication by animals would be significantly limited by the higher background noise in the open ocean. Measures of long-term sea noise trends highlight the influence of biological sources and the importance of local sound transmission regimens.

Keywords Sea noise • Ambient • Ocean noise • Sound transmission

1 Introduction

Ambient noise in the ocean is generally considered to be the background noise from all sources except for identifiable localized sources such as a ship or a whale but may include noise from large numbers of animals and distant ships (Wenz 1962; Urick 1983). Ambient noise may be produced by a myriad of sources, generally broken down into categories of natural biological, natural physical, and man-made origin. An extensive literature exists on ambient noise. The noise sources act with the local and regional sound transmission regimens to determine the local ambient-noise sound field. Sources may be distant or close depending on their intensity and

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the sound transmission. The sound transmission regimen is critical in determining the ambient-noise levels at any site because it dictates the listening area over which sound sources sum and acts as a frequency filter, preferentially passing some frequencies over others (Carey and Evans 2011).

Here we looked at the geographical differences and trends in ambient sea noise waters along the southern Australia coast. Receivers were moored on the continental shelf edge so that they coupled acoustically to the Southern Ocean via the deep sound channel while other receivers were moored over the same time period on the continental shelf back from the shelf edge. This setup can be used to highlight the effects on ambient noise of different sound transmission regimens. Sea noise was sampled from 2001 to 2013 from one general location, allowing us to look at long-term changes in average sea noise levels. Relatively few ships pass through the Southern Ocean south of Australia so most noise sources are natural.

2 Methods

2.1 Sea Noise Recording Hardware

Sea noise loggers were placed on the seafloor. On some moorings, multiple instruments at the seafloor were used for redundancy. Details of the locations are listed in Table 83.1. The mooring arrangement was designed to isolate the hydrophone from the movement of the mooring line. In all deployments, the hydrophone was external to the housing containing the system electronics and batteries and lay freely on the seabed. All datasets used sea noise loggers built at Curtin University (see http://cmst.curtin.edu.au/products/usr.cfm for specifications). These sea noise loggers comprised an external, factory-calibrated hydrophone, either a HiTek HTI U90, Massa TR1025C, or, on occasion, a General Instruments C-32, entering the housing with data sampled at 6 kHz, written to a flash card, and then transferred to IDE hard drives in PC-readable format using an intermittent sampling schedule (200- to 500-s sample length, taken every 900 s). A low-frequency roll-off below 20–100 Hz (depending on the hydrophone) was used to "flatten" the system dynamic range. Antialiasing filters were set at 0.47 times the sampling frequency. The frequency response of all systems was calibrated from 1 Hz to the Nyquist frequency using white noise of a known level input with the hydrophone in series. The system frequency response was fully recovered during analysis here in the frequency domain. Recording system clocks were set to GPS-transmitted coordinated universal time (UTC) before deployment and the drift was read after recovery against GPS-transmitted UTC for instrument timing errors of ±250 ms.

Table 83.1 Locations of receivers, water depths, and distance inside a 200-m-deep contour or continental shelf break

Location	Latitude (S)	Longitude (E)	Water depth (m)	Distance to shelf break (km)
1	31°53.7′	130°39.0′	50	162
2	33°21.5′	130°40.5′	190	0.1
3	38°47.6′	142°15.9′	90	11.9
4	37°20.3′	139°17.0′	138	5.6
5	38°33.6′	141°15.1′	168	3.5

2.2 Receiver Locations

Receivers used to compare on-shelf versus off-shelf edge receivers were those at locations 1 and 2 in Table 83.1. Location 1 was well back up on the continental shelf that was gently sloping toward it and 163 km north of location 2. Receivers used to look at long-time series trends were those at locations 2–5 in Table 83.1. All receivers were used to give an indication of sea noise sources.

2.3 Analysis and Unit Conventions

All analysis was carried out in the MATLAB environment using in-house software. Time-averaged spectra were obtained from each noise logger sample over the sample duration (200–500 s depending on the receiver). The samples were always made 15 min apart. Noise artifacts were generally low because the sea noise loggers were set on the seabed decoupled from the mooring. When artifacts occurred, they were removed from the time-averaged spectra using a despiking process that discarded any individual power spectra with high energy. Time-averaged power spectra were made at resolutions of 65,536 points, 8,192 points, and 512 points within a sample with no overlap and a Hanning window, checked for noise artifact spikes with any "noisy" power spectra discarded, averaged across a sample, and then calibrated to units of decibels re 1 $\mu Pa^2/Hz$ using the frequency-dependent calibration curve. Pseudo 1/3 octaves were obtained for each sample by using the respective 1/3-octave bands, an appropriate frequency resolution, summing the power spectra intensity within the 1/3-octave band, and correcting for bandwidths. All units presented here are spectral units (in dB re 1 $\mu Pa^2/Hz$).

All spatial analysis used the MATLAB mapping toolbox with great circle paths. Bathymetry was derived from the Geoscience Australia 1-km grid (http://www.ga.gov.au/marine/bathymetry.html). All locations use a reference datum of WGA 84.

3 Results and Discussion

3.1 Natural Sea Noise Sources Present

A large variety of natural sea noise sources was present across all sites. Natural sea noise sources included ice cracking, far Southern Ocean wind noise, natural seismic events, wind, rain, Antarctic blue whales, pygmy blue whales, fin whales, humpback whales, Antarctic minke whales, southern right whales, unidentified great whale signals, and a variety of fish choruses and fish calls. These signals and their impact on ambient noise are not considered in detail here.

3.2 Difference between Simultaneous Continental Shelf and Shelf Break Sea Noise

Receivers at locations 1 and 2 (Table 83.1) ran simultaneously with two receivers set at each location. Each pair of receivers at each location gave the same results within 1 dB in the time-averaged spectra so data from only one receiver per site is shown. A series of time-averaged spectra made sequentially across a 1.5-h period from 1145 to 1315 h (Australian Central Standard Time; UTC + 8 h) on 18 November 2011 is shown in Fig. 83.1a. The spike at 25–26 Hz was due to nearby whales calling at each site and is not discussed here. Comparing the 2 sites, the sea noise spectra trends were approximately similar below 5 Hz and above 126 Hz when considering the probable slightly different weather conditions (e.g., wind speeds) between the sites. But the two sites were considerably different in spectral content between 5 and 126 Hz by as much as 25 dB across 10–20 Hz. This difference in spectral content occurred consistently when comparing the two sites (over a 12-month deployment), with the site set back on the shelf edge quieter over the 5- to 120-Hz frequency band than the shelf break site.

In deep water, much of the energy in the frequency band of 5–120 Hz is that associated with energy ducted in the deep sound channel (Urick 1983), suggesting that the shelf break noise logger was receiving energy from the deep sound channel while the receiver set back on the shelf was not. To investigate if this was the case, a simple sound transmission scenario to highlight ray paths leading onto the continental shelf was run. To set up the sound transmission model, a winter sound speed profile was derived from temperature, salinity, and depth values extracted from the World Ocean Atlas for 40° S 130°30′ E (National Oceanographic Data Center, National Oceanic and Atmospheric Administration; http://www.nodc.noaa.gov/OC5/WOA05/pr_woa05.html) with the profile shown in Fig. 81.1b. The bathymetry along a path running 955 km due south of the northern receiver location was interpolated from the Geoscience Australia bathymetry dataset. A sound transmission-modeling interface, acoustic toolbox user-interface and postprocessor (AcTUP; Centre for Marine Science and Technology, Curtin University; http://cmst.

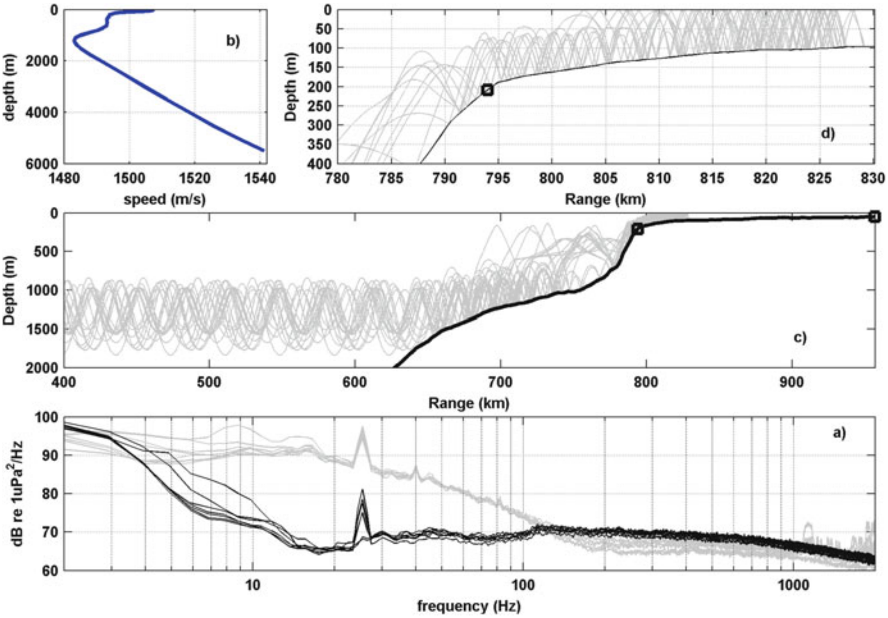

Fig. 83.1 (**a**) Measured time-averaged sea-noise spectra made from a site on the continental shelf edge in the Great Australian Bight (*gray lines*) compared with time-averaged spectra made over the same time period from a site 163 km north of this on the continental shelf. (**b**) Sound speed profile used in BELLHOP modeling. (**c**) Output of BELLHOP ray-tracing model showing 20 ray paths of a 50-Hz signal propagating along the deep sound channel axis in deep water as the rays strike the continental shelf break and back onto the shelf. *Square*, location of receivers; *black line*, seafloor. (**d**) Expansion of the BELLHOP ray paths traveling up the shelf break. The rays eventually become too steep and do not transmit further than ~35 km back onto the shelf

curtin.edu.au/products/actoolbox.cfm), was used with the sound speed and bathymetry profiles plus a simple seabed of sand (50 m deep) over a hard basement, source depths of 50 and 1,000 m, and frequencies of 20, 50, and 80 Hz for running the ray-tracing model Bellhop (Porter 2011) north onto the continental shelf. The model was run with a simple seabed estimate only to illustrate ray paths and thus infer the relative loss to the different receivers. The model output using a 50-Hz source located near the sound speed minimum axis (1,000 m depth) of the ten longest traveling rays heading up the continental shelf edge and onto the shelf is shown in Fig. 83.1c with the full 955-km path shown in Fig. 83.1d (20 longest traveling rays only shown from a starting bundle of 2,000 rays using takeoff angles from +10° to −10°). It is apparent from the ray paths shown in Fig. 83.1c, d, that as the deep sound channel-ducted energy strikes the continental shelf edge, the rays are reflected up and then refracted or reflected down at increasingly steep angles as they move further up into shallow water. There is a focusing area along the shelf slope where the rays become packed closer together as their respective paths steepen (in the vertical plane). As the rays move upslope, they eventually become too steep to transmit horizontally, with all of their energy transmitting directly into the seabed and almost none reflecting. This can be seen in Fig. 83.1c where the BELLHOP model has removed rays once they became too steep to travel laterally, leaving only a few paths making it onto the shelf. In the example shown, the loss of ray paths indicate that very little energy has made it onto the continental shelf and what energy has made it onto the shelf has steep vertical ray paths and therefore did not travel far onto the shelf. The situation was considerably worse for a distant source that was near the sea surface (50 m depth; 20, 50, and 80 Hz) and not at the sound channel axis (as shown in Fig. 83.1c, d), in that the focusing along the shelf edge and the increasingly steep ray paths again occurred on moving upslope, but in this case, no transmitting rays at all made it onto the shelf break. Thus the difference we consistently observed in ambient-noise levels between the site inside the continental shelf edge and at the shelf edge over the 5- to 120-Hz frequency band is consistent with the loss of deep sound channel energy transmitted back onto the continental shelf. The shelf break sea noise logger was receiving deep sound channel-ducted energy in the focusing region along the shelf break, whereas the receiver on the continental shelf well back inside the shelf break did not receive this energy.

This loss of deep sound channel energy transmitted back inside the continental shelf edge will be applicable in any of the world's oceans, thus providing relative isolation from distant sources for receivers up on the shelf.

The transmission of signals from the deep ocean up the continental shelf slope thus (1) results in ray paths steepening in the vertical plane as they travel upslope to the point where they cannot travel laterally; (2) creates a "focusing" area somewhere along the continental shelf edge by converging the ray paths; (3) results in rapidly increasing losses of energy from the propagating signal as it moves upslope due to the increasing number of bottom interactions; and (4) generally largely removes ocean-generated sound energy from traveling far on to the continental shelf. The modeling example shown was simplistic and specific for the scenario modeled, but the resulting trends have been routinely observed by the authors in more complex modeling examples, such as for air gun energy produced in the deep ocean that does not transmit back onto the continental shelf. The trends will also apply to biological signals generated in the deep ocean, such as whale signals.

The results imply that marine fauna transitting across a continental shelf from deep water will notice an increase in sound energy in the 5- to 120-Hz band and an increase in the vertical directionality of long-range ocean noise signals as they move across the shelf slope and then a rapid decline in energy once they move into shallow slope waters or cross up onto the continental shelf. All of these features will offer significant cues to the animal as to where they are with respect the deep ocean.

Opportunities for long-range transmission offered by the sound channel in the deep ocean would be significantly offset by the masking of the much higher background noise for communication signals below 120 Hz. The loss of sound energy in the 5- to 120-Hz frequency band back up on the continental shelf will offer a "quiet" environment for oceanic whales, removing the continual contribution of ambient-noise energy at the ocean scale and bringing the ambient-noise levels back to the scale that the local sound transmission regimen enables, perhaps only tens of kilometers.

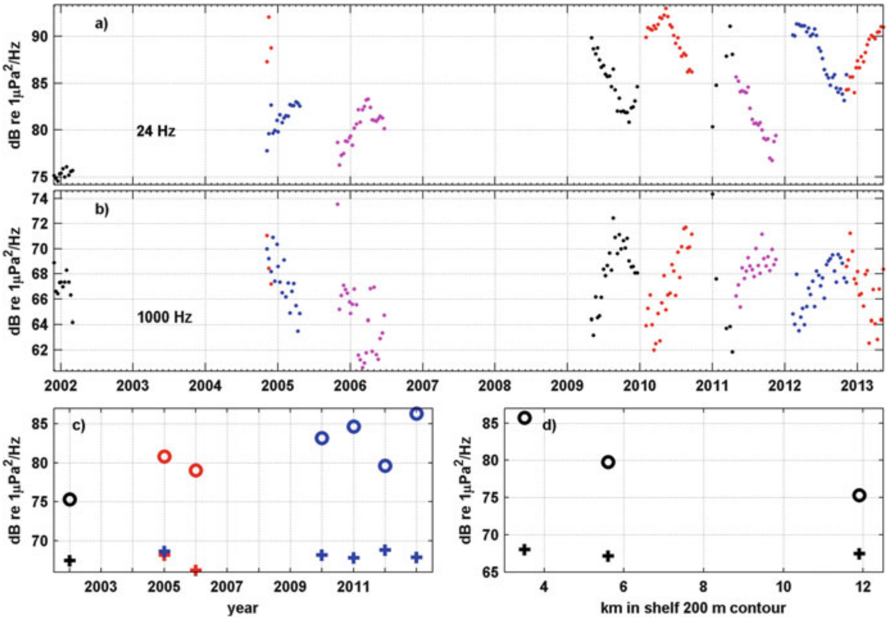

Fig. 83.2 (**a**) Median spectral levels in the 24-Hz 1/3 octave made across 10-day periods starting at the beginning of each calendar year for all data. *Colors* represent different deployment sets. (**b**) Median spectral levels in the 1-kHz 1/3 octave made across 10-day periods starting at the beginning of each calendar year for all data. (**c**) Median spectral level values made across periods spanning 40 days on each side of the calendar year start. *Circles*, 24-Hz octave; *plus signs*, 1-kHz 1/3 octave. Locations in Table 83.1: *black*, location 3; *red*, location 4; *blue*, location 5. (**d**) Median spectral level values made across all periods spanning 40 days on each side of a calendar year start for locations in Table 83.1

3.3 Long-term Trends in Sea Noise

To investigate long-term sea noise trends, multiple datasets from sites 3 to 5 in Table 83.1 were used. All datasets were perused in 5-day stacked spectrograms and periods with noise artifacts were removed completely from the analysis. The time-averaged spectra for each dataset were used to create pseudo 1/3 octaves across center frequencies of 5 Hz to 2 kHz. To display long-term trends, data in 1/3 octaves for each recording set were grouped into 10-day periods and the median spectral-level 1/3-octave value for each 1/3-octave frequency band was derived. These median level 1/3-octave values are displayed for the center frequencies of 24 Hz and 1 kHz in Fig. 83.2a, b, respectively. These frequencies highlight biological sea noise sources, the 24-Hz 1/3-octave band (with a bandwidth of 22.1–27.8 Hz) spans the bandwidth of Antarctic blue whale calls, and the low-frequency portion of pygmy blue whale calls (i.e., Gavrilov et al. 2011, 2012; Gavrilov and McCauley 2013), whereas the 1-kHz 1/3-octave bandwidth (890.9–1,122 Hz) spans a regular fish chorus observed along the shelf of southern Australia. The blue whale calling and fish choruses have well-defined seasonal patterns of occurrence in Australian waters and so seasonal calling habits that are clearly evident as the cyclical changes in level (8–15 dB across a season) as seen in Fig. 83.2a, b. The long-term level trends also exhibit interseasonal differences in the levels reached. These interseasonal changes in level are not explored here.

On looking at the long-term trends with time shown in Fig. 83.2a, b, there is no clearly evident change in the 1-kHz 1/3 octave, but there is the suggestion of an increase in the 24-Hz 1/3-octave level with increasing time. To highlight long-term changes in the 1-kHz and 24-Hz 1/3 octaves, the datasets were consolidated for each location and median values were calculated at each 1/3 octave for 40 days spanning each new year for the years 2002–2013. The resulting values are shown in Fig. 83.2c for the 24-Hz and 1-kHz 1/3 octaves. An increase in the 24-Hz 1/3 octave with time is clear in Fig. 83.2c, but no trend is apparent for the 1-kHz 1/3 octave. But this ignores the issue highlighted in Section 3.1 of energy transmitting from the deep ocean up the continental shelf being rapidly stripped away as it travels upslope. The 24-Hz whale signal energy primarily originated in the deep ocean or along the shelf edge and receivers 3–5 were located at different distances in from the shelf edge (Table 83.1). Thus as a check on how the distance in from the shelf edge correlated with the level in each 1/3 octave, the median value of all data from each site spanning 40 days at the turn of each year was found and plotted with distance in from the shelf break. These values are shown in Fig. 83.2d for the 24-Hz and 1-kHz 1/3 octaves. There was a clear drop with distance in from the shelf break for the 24-Hz 1/3 octave, suggesting that the change in level apparent in Fig. 83.1a, c, for the 24-Hz 1/3 octave was in fact due to energy loss on moving upslope rather than a time-related increase in noise. When looking at all 1/3-octave frequencies (5 Hz to 2 kHz) and a drop in level correlating with the distance in from the shelf edge, correlations became apparent at the onset of great whale calling energy (the 12-Hz 1/3 octave) and had dropped away at frequencies above oceanic whale calling, by the 200-Hz 1/3 octave. As displayed in Fig. 83.1d for the 1-kHz 1/3 octave, there was no correlation of 1/3-octave levels with distance in from the shelf break or time above the 800-Hz 1/3 octave.

This example of long-term trends in noise levels has been included to highlight (1) that biological sources regularly make large differences to ambient sea noise on the order of 10–15 dB at the seasonal scale shown here but upward of 35 dB on a daily scale in some cases (McCauley 2012) and (2) that interpreting ambient noise along the continental shelf edge is fraught with problems related to the rapid loss of energy that occurs for oceanic sound sources traveling up and onto the continental shelf.

4 Summary

Sea noise loggers set back inside the continental shelf break and simultaneously at the shelf edge highlighted a large (up to 25-dB) difference in ambient noise over a portion of the bandwidth transmitted by the deep sound channel (5–120 Hz here). The sea noise 163 km back inside the shelf break was consistently quieter than the shelf break noise logger across this frequency band.

Sound transmission modeling of a source transmitting along the deep sound channel axis and traveling up the continental shelf slope highlighted that energy was quickly lost as it moved upslope by increasing interactions with the seabed. The ray paths steepened with each seabed reflection as they moved upslope until eventually the paths could not travel laterally. Little, if any, of this ocean-ducted signal reached the continental shelf. There was a convergence zone for ray paths along the continental shelf edge where sound levels were likely to increase due to ray paths converging, but on moving further upslope, energy was quickly lost. An open-ocean source near the surface and ducted into the deep sound channel from long range suffered worse attenuation on reaching the continental shelf edge than a source near the sound channel axis. This was due to a shallow source having the ray paths trapped by the deep sound channel at steeper angles to the vertical than for a source at a depth near the sound channel axis.

This phenomenon of a loss of ocean energy for signals traveling up onto the continental slope would be consistent worldwide and implies that measurements of deep ocean sound energy in continental shelf waters will not accurately reflect oceanic ambient-noise regimens below ~200 Hz. In continental shelf waters, energy below 200 Hz will be dictated by nearby sound sources in this frequency band and the local sound transmission regimen, not by sources at an ocean basin scale as for the deep ocean.

An example of long-term sea noise highlighted the importance of biological sources in many frequency bands at the seasonal scale here and reiterated the complexity of interpreting changes in ocean noise for receivers set across or just inside the continental shelf break.

Biological receivers moving into shallow water across a continental slope will notice (1) an initial increase in sound channel-ducted energy, then a rapid decline of this, and (2) a steepening of ray paths for energy below 200 Hz, matching the increase and then a decrease in this signal energy. Continental shelf waters offer a “quiet” environment free of ocean-scale deep sound channel energy.

Acknowledgments BP Developments Australia Pty. Ltd. supported sea noise logger deployments at locations 1 and 2. Santos, Origin Energy, Woodside Energy, Primary Industry Research South Australia (PIRSA), Benaris, and Essential Oil funded early noise logger deployments from locations 3 to 5. Sea noise logger deployments from 2008 onward at location 5 (south of Portland) were funded by the Australian Governments’ Integrated Marine Observing System (IMOS), a part of the National Collaborative Research Infrastructure Scheme (NCRIS).

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Chapter 84
Spatial Patterns of Inshore Marine Soundscapes

Jamie McWilliam

Abstract Passive acoustic monitoring was employed to investigate spatial patterns of soundscapes within a marine reserve. High energy level broadband snaps dominated nearly all habitat soundscapes. Snaps, the principal acoustic feature of soundscapes, were primarily responsible for the observed spatial patterns, and soundscapes appeared to retain a level of compositional and configurational stability. In the presence of high-level broadband snaps, soundscape composition was more influenced by geographic location than habitat type. Future research should focus on investigating the spatial patterns of soundscapes across a wider range of coastal and offshore seascapes containing a variety of distinct ecosystems and habitats.

Keywords Underwater sound • Acoustic composition • Snapping shrimp • Environmental monitoring

1 Introduction

How do we define a soundscape? How does it relate to the seascape? Soundscapes are an integral component of marine environments where many organisms use sound to communicate, navigate, and forage. Sound underwater is propagated over large distances so that acoustic horizons far exceed visual horizons, causing seascapes to be far more connected acoustically than optically. This highlights the opportunity of using passive acoustic monitoring (PAM) as a method for measuring environmental change over multiple spatial scales. In marine soundscape research, spatial investigations of acoustic data have seen limited application but are essential for developing our understanding of soundscapes and, in particular, determining the functional roles of soundscapes within marine ecosystems. The goal of this work was to investigate spatial patterns of soundscapes in an inshore marine reserve, exploring PAM as an ecological monitoring tool.

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2 Methodology

Soundscape investigations were carried out over two separate field studies, conducted first in May 2012 and continued in March 2013. To enable the investigation of scale-related acoustic patterns, an interdisciplinary survey approach was employed in which a combination of georeferenced acoustic, biological, and geomorphological data was collected.

2.1 Initial Study

During May 2012, 45 individual acoustic recordings were taken in three different benthic habitats, Mud, Cliff, and Gravel in Lough Hyne, a marine reserve located in the south of Ireland. The habitats were identified by using a combination of underwater video, sonar, and consultation of previous diver survey data. A hierarchical sampling design was employed to allow a comparison of soundscapes at different spatial scales (habitat, $n=3$; patch, $n=3$; site, $n=5$). The soundscape of each site was described quantitatively by calculating sound spectrum levels and snap incidence from a 1-min subsample. The number of snaps was calculated using a signal threshold count technique. For additional quantitative measures of soundscapes, see McWilliam and Hawkins (2013). To determine how environmental variables may have influenced the spatial composition of soundscapes, a Pearson's correlation coefficient was carried out on selected environmental variables.

2.2 Follow-up Study

The follow-up study had two main objectives: (1) reassess the compositional stability and coverage of soundscapes and (2) review the position of the suspected dominant sound source. In March 2013, 85 individual geotagged acoustic recordings were taken at selected sites around the Lough using a hydrophone suspended from an antiheave buoy designed to minimize extraneous noise from surface swell. Following the findings from the initial study, which revealed that broadband impulsive sounds constituted a key component of soundscapes, snaps were chosen as indicators of soundscape composition. The number of snaps and corresponding amplitudes were calculated from a 30-s subsample selected from each site recording using the same signal threshold count technique employed in the initial study. Snap amplitude values were then assigned to five selected bands and projected onto a map.

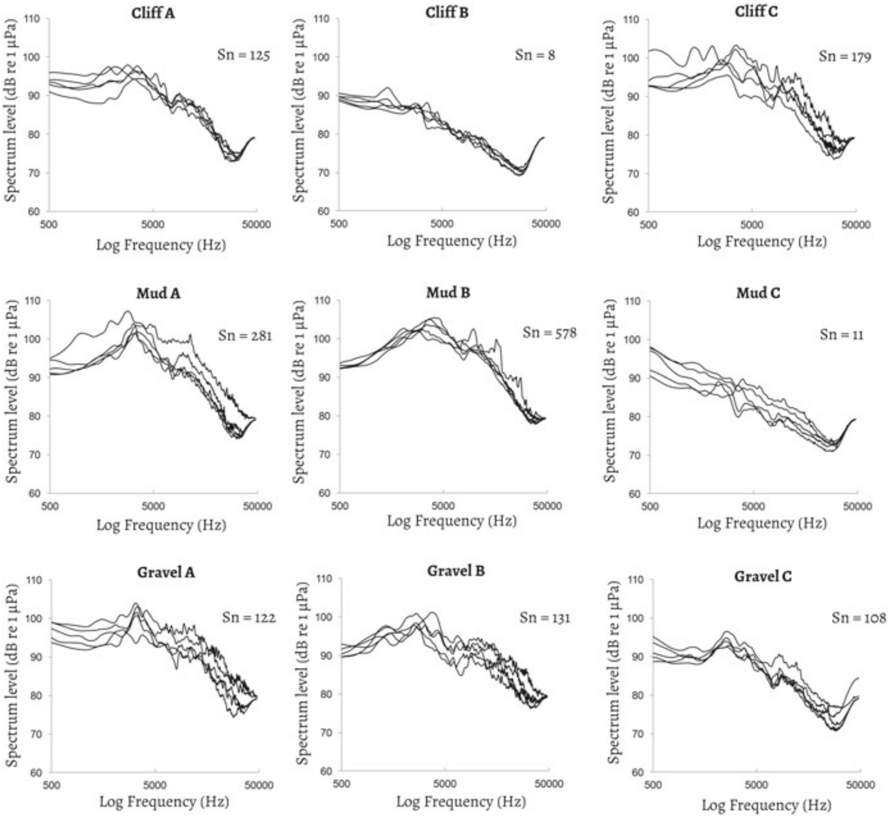

Fig. 84.1 Power spectra for the five sites within each habitat patch. *Sn* average snap count. Adapted from McWilliam and Hawkins (2013)

3 Results

3.1 Acoustic Features of Soundscapes

The main acoustic feature of soundscapes was high-level broadband snaps, which exhibited a continual 24-h presence. Snaps were present in all habitat soundscapes and dominated the majority of site soundscapes. For a number of recording sites situated in the south basin, snaps were so dominant that they masked other background sounds, including those of suspected biological origin that were detected through passive listening and visual spectrogram analysis. A distinct peak in acoustic energy over 2- to 4-kHz frequency bands was observed in all but one of the habitat patches (Fig. 84.1).

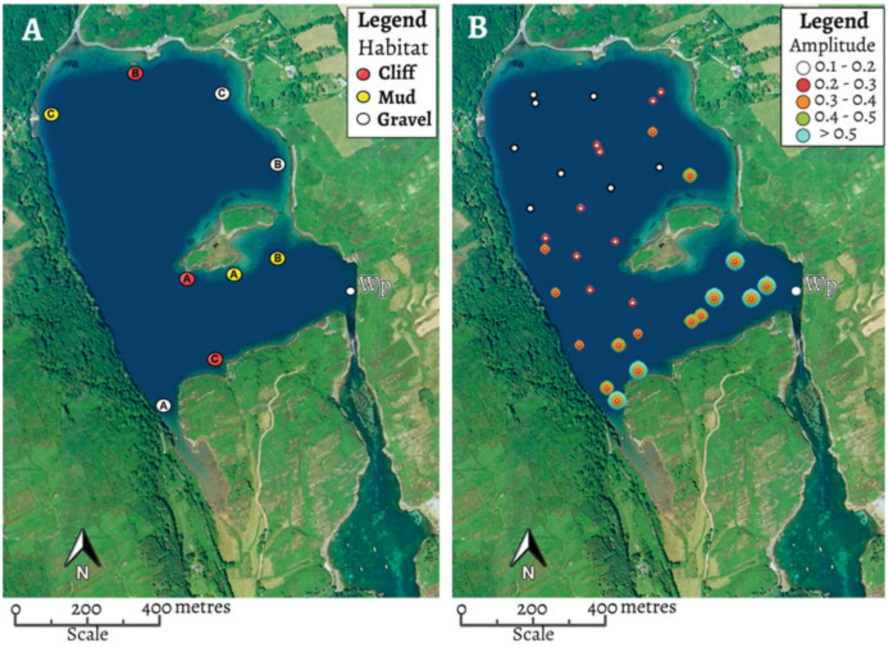

Fig. 84.2 (**a**) Georeferenced aerial map of habitat locations. *A*, *B* and *C* in circles, the three patches selected for each habitat. (**b**) Frequency distribution of snap amplitudes at selected survey sites. *Wp* whirlpool cliffs, location of main source of snaps

Comparison of Soundscapes

A degree of acoustic stability appeared to exist between the selected sites at patch level (Fig. 84.1). There was a positive relationship between acoustic energy and snap number, showing that snaps contributed significantly to raising the sound level at the sites. Mud B, located in the southern area of the Lough, displayed one of the highest snap frequencies and sound pressure spectrum levels of all the sites, whereas Mud C, situated at the top of the north basin, exhibited the lowest levels (Fig. 84.2). Although there were noticeable similarities within habitats, a nested ANOVA revealed that with the exception of the Gravel habitat, there were significant differences between snap number and corresponding habitats for both the Mud and Cliff habitats.

A significant correlation was observed between the number of snaps and the distance to the Whirlpool Cliffs, indicating that the spatial patterning of soundscapes within the Lough appeared to be more influenced by proximity to high-level broadband sound sources than by the underlying benthic habitat composition, where bottom hardness, a proxy for bottom type, influenced soundscape composition to a lesser degree (Table 84.1). No significant relationship was found between depth and snap number.

Table 84.1 Pearson's correlation coefficients between snap number and environmental variables

Comparison	Patch ($n = 15$)	Site ($n = 45$)
Depth	0.14	0.07
Bottom hardness	0.51	0.37*
Distance to Whirlpool cliffs	–0.79*	–0.76**

*$P < 0.05$; **$P < 0.01$

3.2 Follow-up Study

Soundscape Composition

The composition of soundscapes within the Lough appeared to remain stable, with snaps retaining their position as the primary acoustic feature.

Spatial Patterns of Soundscapes

The spatial patterns of the soundscapes within the Lough displayed a strong degree of continuity. The dominance of the soundscapes in the South Basin by numerous high-level snaps, contrasting with fewer low-level snaps in the North Basin, matched the findings of the initial study (Fig. 84.2). With the exception of two outliers in the southwest of the Lough, the sites nearest to the Whirlpool Cliff, the suspected source of the snaps, contained the highest snap amplitudes, corresponding with the site recordings taken in March 2013.

4 Discussion

It is evident that snaps represent an important acoustic feature of soundscapes in Lough Hyne. In the presence of high-level broadband snaps emanating from particular sites, geographic location is a more important factor influencing soundscape composition than habitat type. Further consultation of a long-term data series from an autonomous loggerhead acoustic buoy stationed in the Lough revealed that snaps are present all year-round, thus demonstrating that they represent a permanent feature of the local soundscapes.

A review of past research suggests that the snaps are produced by members of the *Alpheus* genus, an invertebrate commonly known as the snapping or pistol shrimp. The observed 2- to 4-kHz energy peak and underlying waveform both correspond to the characteristic snapping sounds of *Alpheus* described by Versluis et al. (2000), indicating that these invertebrates are the primary sound source.

4.1 Spatial Dynamics of Soundscapes

Snaps were predominantly responsible for the spatial patterns of the soundscapes within the Lough. Observations made in the follow-up study revealed that these spatial patterns appear to remain relatively stable, whereas snaps detected in the North Basin sites are likely to be the attenuated remnants of snaps originating from the Whirlpool Cliffs located in the South Basin. A number of high-level snaps were detected in the southwest of the Lough, which indicated that there were other groups of *Alpheus* species. The high spatial connectedness of the soundscapes is thought to result from a combination of the Lough's size and the acoustic properties of a snap. At larger spatial scales in less sheltered coastal and offshore seascapes, this acoustic connectedness may not be so apparent, and geophonic and anthrophonic sounds may have a greater presence in soundscapes. Sounds made by snapping shrimp are among the most widespread sources of sound in tropical and subtropical waters, and it is now evident that their presence also extends to some temperate waters (Johnson et al. 1947; Finfer et al. 2007; Coates et al. 2012). Studies carried out by Kennedy et al. (2010) and Baumann-Pickering et al. (2011) in Pacific Panama and the north Pacific both observed the same distinct spectrum peak, with acoustic energy concentrated around 3 kHz as seen in Lough Hyne. This suggests that sounds produced by *Alpheus* species could provide the underlying biophonic framework of many marine soundscapes.

4.2 Surveying Marine Soundscapes

The snap frequency distribution map shown in Fig. 84.2 illustrates the considerable heterogeneity of soundscapes over a comparatively small area. This highlights the need for greater spatial coverage in soundscape studies, particularly when scaling up acoustic data to estimate the surrounding soundscapes. To adequately gauge the underlying spatial patterns of marine soundscapes, multiple point recordings over a range of spatial scales, extending from a few meters to several kilometers, are required. This is particularly so when investigating shallow seascapes such as coral reefs where benthic topographic complexity is likely to significantly increase soundscape heterogeneity at relatively small spatial scales (Lindholm et al. 2009).

4.3 Future Soundscape Research

Future research should focus on using PAM to investigate the spatial dynamics of soundscapes across a wider range of spatial scales, selecting and comparing contrasting seascapes that contain a variety of distinct ecosystems and habitats. It is also urged that there should be a stronger emphasis on investigating the possible ecological functions of snaps within marine ecosystems.

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Chapter 85
Soundscape and Noise Exposure Monitoring in a Marine Protected Area Using Shipping Data and Time-Lapse Footage

Nathan D. Merchant, Enrico Pirotta, Tim R. Barton, and Paul M. Thompson

Abstract We review recent work that developed new techniques for underwater noise assessment that integrate acoustic monitoring with automatic identification system (AIS) shipping data and time-lapse video, meteorological, and tidal data. Two sites were studied within the Moray Firth Special Area of Conservation (SAC) for bottlenose dolphins, where increased shipping traffic is expected from construction of offshore wind farms outside the SAC. Noise exposure varied markedly between the sites, and natural and anthropogenic contributions were characterized using multiple data sources. At one site, AIS-operating vessels accounted for total cumulative sound exposure (0.1–10 kHz), suggesting that noise modeling using the AIS would be feasible.

Keywords Ship noise • Renewable energy • Automatic identification system data • Marine mammals • Acoustic disturbance

1 Introduction

Underwater noise levels in the open ocean have been rising since at least the 1960s due to increases in shipping (Andrew et al. 2002) correlated to global economic growth (Frisk 2012). Closer to shore, escalations in human activity such as shipping, pile driving, and seismic surveys have transformed coastal marine soundscapes (Hildebrand 2009), with uncertain consequences for the ecosystems that inhabit them. These large-scale changes in the acoustic environment are of particular concern for marine mammals (Tyack 2008), which rely on sound as their

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primary sensory mode. Noise has the potential to mask important acoustic cues in marine mammal habitats, such as echolocation and communication (Jensen et al. 2009), and may disrupt prey (Popper et al. 2003), affecting foraging. These anthropogenic pressures may lead to physiological stress (Wright et al. 2007; Rolland et al. 2012), habitat degradation, and changes in behavior (Nowacek et al. 2007). The cumulative cost of these responses can alter the animals' activity budget (Lusseau 2003), which may have downstream consequences for individual vital rates and, ultimately, population dynamics. Efforts are underway to develop a framework to predict such population consequences of acoustic disturbance (PCAD; National Research Council 2005).

Recently, we conducted studies to characterize key contributors to underwater noise levels in the inner Moray Firth, a Special Area of Conservation (SAC) for a resident population of bottlenose dolphins (*Tursiops truncatus*) and an important habitat for several other marine mammal species (Merchant et al. 2014). We advanced methods for ship-noise monitoring by combining automatic identification system (AIS) ship-tracking data and shore-based time-lapse video footage and explored whether underwater noise modeling based on AIS data could accurately predict noise levels in the SAC. These methods can be applied in other coastal regions to evaluate the contribution of vessel noise to marine soundscapes.

2 Study Site and Methods

The inner Moray Firth is a SAC for bottlenose dolphins, and long-term monitoring of the population's size suggests that it is stable or increasing (Cheney et al. 2013). Other marine mammal species in the area include the harbor seal (*Phoca vitulina*), harbor porpoise (*Phocoena phocoena*), and gray seal (*Halichoerus grypus*). The Moray Firth is expected to become an important base for the development of Scotland's expanding offshore renewables industry, increasing levels of vessel traffic to fabrication yards and ports within the SAC (New et al. 2013).

Two locations were selected for underwater noise monitoring: The Sutors (57°41.15′ N, 3°59.88′ W), at the entrance to the Cromarty Firth, and Chanonry (57°35.12′ N, 4°05.41′ W), to the southwest (Fig. 85.1). Both sites are deep narrow channels characterized by steep seabed gradients and strong tidal currents, heavily used by the dolphins for foraging (Hastie et al. 2004; Bailey and Thompson 2010; Pirotta et al. 2014). The Sutors supports commercial ship traffic transitting in and out of the Cromarty Firth, whereas Chanonry is en route to Inverness and the west coast of Scotland via the Caledonian Canal.

Several deployments of single passive acoustic monitoring (PAM) devices (Wildlife Acoustics SM2M) were made at the two sites during summer 2012. Noise was monitored on a duty cycle of 1 min every 10 min at a sampling rate of 384 kHz, 16 bits. This allowed for detection of ship passages with a similar time resolution to the AIS data (~10 min; see below) while also providing recordings of marine

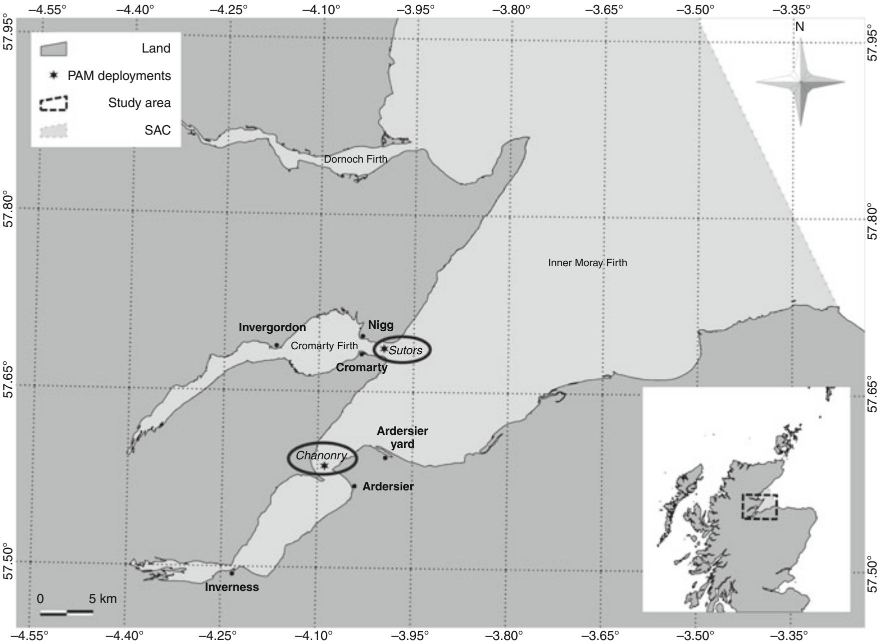

Fig. 85.1 Map of the inner Moray Firth. Ellipses denote deployment locations. *PAM* passive acoustic monitoring, *SAC* Special Area of Conservation

mammal sounds up to 192 kHz. The manufacturer's frequency-dependent sensitivity, which agreed with an independent calibration to within ±1 dB in the range of 25–315 Hz, was used to calibrate the PAM data for the entire frequency range (25 Hz to 192 kHz). Spectral analysis revealed low-amplitude tonal noise from the PAM system at various frequencies above 1 kHz (Merchant et al. 2013). This system noise contaminated a small proportion of the frequency spectrum (<0.1%) and was omitted from the analysis.

AIS ship-tracking data were provided by a Web-based ship-tracking network (http://www.shipais.com/) for the duration of the deployments. Time-lapse footage was also recorded using shore-based digital cameras (Brinno Gardenwatchcam GWC100) whose field of view encompassed the PAM locations. Peaks in the broadband noise level were attributed to AIS vessel movements via the technique developed by Merchant et al. (2012), using a narrower frequency range (0.1–1 kHz, not 0.01–1 kHz) due to low-frequency flow noise and a higher threshold ceiling (12 dB, not 6 dB) to exclude nonship-generated noise from the nearby shipyard. AIS analysis was conducted for The Sutors, which had the best (>80%) temporal coverage. By comparing AIS vessel movements with the acoustic data, noise peaks were classified as due to (1) the closest points of approach (CPAs) of vessel passages, (2) other AIS vessel movements, and (3) unidentified.

3 Baseline Noise Levels

Ambient noise levels differed significantly between the two sites. Compared with The Sutors, noise levels at Chanonry were relatively low, with only occasional vessel passages. Variability in ambient noise levels at Chanonry was largely attributable to weather and tidal processes. Noise levels at The Sutors were highly variable in the range of 25 Hz to 1 kHz, and the spectrum featured more frequent vessel passages than Chanonry. There were also two instances of rigs being moored within or towed past The Sutors: first, between 16 and 23 June, and the second at the end of the final deployment on 27 September. The vessels towing and positioning the rigs (using dynamic positioning [DP]) produced sustained, high-amplitude broadband noise concentrated below ~1 kHz.

4 Monitoring Future Ship Noise Trends

4.1 AIS Analysis

Analysis of the AIS vessel movements in relation to the peaks recorded at broadband (0.1–1 kHz) noise levels at The Sutors site (see Fig. 85.2) identified 62% of the peaks as due to AIS vessel movements, with 38% unidentified. This was a similar ratio to that reported by Merchant et al. (2012), who observed a ratio of 64% identified to 36% unidentified in Falmouth Bay, UK. The 62% of peaks identified was composed of 52% attributed to vessel CPAs, with the remaining 10% due to other vessel movements such as acceleration from or deceleration to stationary positions.

Modeling of underwater noise levels using AIS data has been proposed as a way to map noise exposure from shipping to facilitate targeted mitigation measures (Erbe et al. 2012). However, the efficacy of such an approach will depend on the proportion of anthropogenic noise exposure produced by vessels with operational AIS transmitters. Vessels below the current 300 GT gross tonnage threshold (International Maritime Organization 2000) not carrying AIS transceivers may also contribute significantly to noise exposure in some areas, and other sources of anthropogenic noise (such as seismic surveys and pile driving) may occasionally be more significant, although their spatiotemporal extent is generally more limited. To investigate the feasibility of AIS noise modeling in the Moray Firth, the sound exposure attributable to AIS-identified and unidentified noise periods for each day of uninterrupted AIS coverage was calculated for The Sutors. These periods were computed as the cumulative sound exposure from the period surrounding a noise peak during which the noise level exceeded the adaptive threshold.

The 24-h sound exposure level (SEL) of each component (total SEL, AIS-identified SEL, and SEL from unidentified peaks) was computed for the range of 0.1–1 kHz. During the presence of the rig-towing vessels operating with a DP from

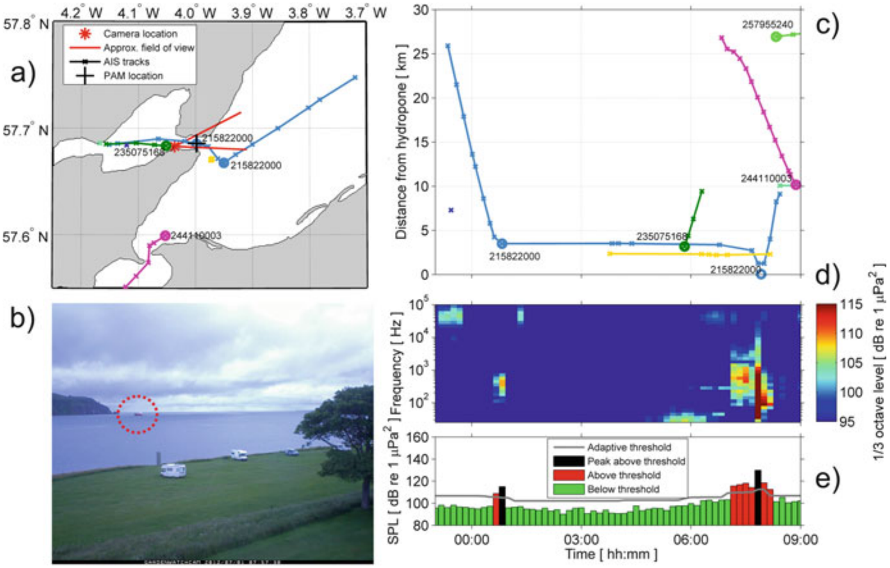

Fig. 85.2 Example of an automatic identification system (AIS) analysis with time-lapse footage (Merchant et al. 2014). (**a**) Map of AIS movements in 6-h period centered on the closest points of approach (CPAs). *Black plus sign* denotes location of PAM unit in The Sutors; *circles* indicate CPAs labeled with Maritime Mobile Service identity (MMSI) number. (**b**) Still of time-lapse footage showing vessel (*circled*) whose CPA occurred at 0750 on 1 July. (**c**) Range of AIS transmissions from PAM unit versus time. (**d**) 1/3-octave spectrum of concurrent acoustic data. (**e**) Broadband level in frequency range of 0.1–1 kHz, showing peak identification using adaptive threshold. *SPL* sound pressure level

16 to 23 June (see Section 3), the noise level was consistently high such that only two peaks were recorded by the adaptive threshold (both AIS identified). Because the rig-towing vessels were using AIS, their presence would be included in an AIS noise model, although their source levels are likely to be significantly elevated by the use of DP, which may not be accounted for by a generic ship source level database. For all but four of the remaining days with uninterrupted AIS coverage, the AIS-identified peaks generated the vast majority of sound exposure recorded in this range. On two of the 4 days (24 June and 8 September), unidentified peaks produced marginally greater sound exposure than AIS-identified peaks, possibly caused by a particularly loud or proximate non-AIS vessel. On 7 and 23 July, no peaks were recorded, and the total 24-h SEL was ~20 dB lower than the minimal levels recorded with detectable ship passages.

Because small vessels (which are not obliged to carry AIS transceivers) may emit noise with peak levels of up to several kilohertz (Kipple and Gabriele 2003), the 24-h SEL in the 1- to 10-kHz bandwidth was also computed to analyze whether higher frequencies were more dependent on unidentified peaks, which are likely to originate from small vessels. This analysis retained the peak classification data used for the 0.1- to 1-kHz range. As expected, the recorded levels were consistently lower than at 0.1–1 kHz. Only 1 day (26 June) showed a significant difference, with unidentified sound exposure more dominant than in the lower frequency band. This demonstrates that sound exposure generated by AIS-carrying vessels at the study site is generally greater than that produced by non-AIS vessels for the range of both frequency bands (0.1–10 kHz). Consequently, a modeling approach based on AIS vessel movements should account for most variability in noise exposure, provided the ship source levels input to the model are sufficiently accurate and acoustic propagation models are sufficiently predictive.

4.2 Time-Lapse Footage

In addition to analysis of AIS movements, time-lapse footage was also reviewed to explore the potential for corroboration of AIS vessel identifications, detection of non-AIS vessels responsible for unidentified noise peaks, and characterization of unusual acoustic events. The frame shown in Fig. 85.2a corresponds to the timing of the noise peak at around 0750 presented in Fig. 85.2c–e and confirms the previous identification of this vessel from the CPA of its AIS track. These data have also been prepared as videos (Merchant et al. 2014), which demonstrate the potential for this method to rapidly review ship movements and underwater noise variability in coastal environments. They also provide an intuitive educational tool to highlight the impact of ship noise on marine soundscapes and the potential for masking, behavioral, and physiological impacts to marine fauna.

5 Discussion

The pairing of shore-based time-lapse footage with acoustic and AIS data provides an important tool for monitoring the influence of human activities on coastal marine soundscapes. The method enabled characterization of abnormally loud events, such as rigs being towed past the deployment site, and facilitated detection of non-AIS vessels responsible for noise peaks and corroboration of AIS-based vessel identification (Fig. 85.2). With improved resolution and field of view, time-lapse monitoring could facilitate more detailed characterization of non-AIS vessels in coastal areas, enhancing understanding of the relative importance of small-vessel traffic to marine noise pollution.

Analysis of noise levels at The Sutors in conjunction with AIS ship-tracking data demonstrated that most sound exposure at the site was attributable to vessels operating with AIS transceivers. This indicates that modeling of cumulative noise exposure based on AIS vessel movements as proposed by Erbe et al. (2012) should account for most of the noise exposure observed experimentally, provided other model parameters (ship source levels, acoustic propagation loss profiles) are sufficiently accurate. This result suggests that models based on planned increases in vessel movements in the Firth (Lusseau et al. 2011; New et al. 2013) may be able to forecast associated increases in noise exposure and is a promising indication that AIS-based noise mapping could be successfully applied to target ship noise mitigation efforts in other marine habitats. However, caution should be exercised in extrapolating from this result because in areas further from commercial shipping activity, the dominant source of ship noise may be smaller craft not operating with AIS transceivers.

These underwater noise measurements also established baseline noise levels within the Moray Firth SAC during the summer field season, providing an important benchmark against which to quantify the acoustic impact of any future changes in anthropogenic noise. Both study sites are important foraging hotspots for the inner Moray Firth bottlenose dolphin population (Hastie et al. 2004; Bailey and Thompson 2010; Pirotta et al. 2014), and C-POD data confirmed regular dolphin presence throughout the deployment periods. Because the population appears to be stable or increasing (Cheney et al. 2013), the current noise levels reported in Merchant et al. (2014) are not expected to threaten the dolphin population level. However, given the marked differences in baseline soundscape between the two sites, any future increases in shipping noise could differentially affect these foraging areas. Although The Sutors is expected to experience greater increases in shipping traffic associated to offshore energy developments, dolphins may already be accustomed to higher noise levels in this area. On the other hand, Chanonry is currently much quieter, meaning that a smaller increase in shipping noise could represent a greater degradation of habitat quality.

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Chapter 86
Global Trends in Ocean Noise

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Abstract This ongoing work provides information about sound level trends from three ocean regions to compare with those of the North Pacific to determine whether increasing sound levels are a global phenomenon. Here the term soundscape is used to describe a measured physical property that can be selectively decomposed by frequency and sound level is used to provide insight relating to conditions ranging from the quietest conditions (sound floor) to the most extreme acoustic events. Acoustic time series from the Indian, South Atlantic, and Equatorial Pacific Oceans were used to quantify the rate and direction of low-frequency change over the past decade.

Keywords Noise • Ambient sound • Soundscape • Sound floor

1 Introduction

Deepwater ambient-sound levels have increased in the North Pacific Ocean over the past 60 years (Ross 1993; Andrew et al. 2002; McDonald et al. 2006; Chapman and Price 2011). The rate of increase was measured at ~3 dB/decade (0.55 dB/year) until the 1980s and then slowed to 0.2 dB/year. The rising sound levels in the North Pacific Ocean have sparked concern about the related environmental impacts as well as whether these trends are indicative of global sound-level increases. Very recent studies have started to contribute information from locations outside the North Pacific Ocean to answer the question of whether the trends observed in the North Pacific Ocean are indicative of an overall global or hemispheric increase in low-frequency ambient noise (Miksis-Olds et al. 2013; van der Schaar et al. 2014). van der Schaar et al. (2014) examined 63-Hz third-octave band sound levels at single stations in each of three oceans (Indian, Pacific, and Atlantic) over 3.5 years in

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response to the European Marine Strategy Framework Directive (European Parliament and the Council of the European Union 2008). Significant differences between annual averages were not clearly identified at any station and trend directions were not consistent; positive, negative, and the absence of any trends were observed (van der Schaar et al. 2014). Miksis-Olds et al. (2013) examined sound levels over the past decade in the Indian Ocean and found that the sound floor was steadily increasing, whereas the median and highest sound levels showed inconsistent changes in magnitude and direction and were a function of frequency.

In addition to examining sound-level trends outside the North Pacific Ocean, the studies by van der Schaar et al. (2014) and Miksis-Olds et al. (2013) both demonstrated the value of using percentiles in characterizing the soundscape and assessing trends. This ongoing work selectively decomposed a long-term time series by frequency and sound-level percentile to provide insight relating to conditions ranging from the quietest conditions (sound floor) to the most extreme acoustic events at a single location in the Indian, South Atlantic, and Equatorial Pacific Oceans. Rate, direction, and magnitude of changes were examined within each percentile as opposed to using the percentiles as only a means to estimate and display variance. The value of using multiple sound-level parameters to assess sound levels, patterns, and trends is demonstrated with a low-frequency (less than −125 Hz) dataset recorded from the Preparatory Commission for the Comprehensive Nuclear Test Ban Treaty Organization (CTBTO) International Monitoring System (IMS).

2 Methods

Acoustics recordings from the CTBTO IMS at Diego Garcia (H08: Indian Ocean), Ascension Island (H10: Atlantic Ocean), and Wake Island (H11: Pacific Ocean) were obtained from the Air Force Tactical Applications Center/US National Data Center (AFTAC/USNDC). Each CTBTO IMS location consists of a triad of hydrophones deployed on opposite sides of an island and positioned in the deep sound channel at a depth of 600–1,400 m depending on location. This work utilized data from the North 1 (N1) hydrophones at each ocean location. Data were sampled continuously at a 250-Hz sampling rate and 24-bit analog-to-digital resolution. The hydrophones were calibrated individually before initial deployment in January 2002 and recalibrated while at sea in 2011. All hydrophones had a flat (3-dB) frequency response from 8 to 100 Hz. Information from individual hydrophone response curves was applied to the data to obtain absolute values over the full frequency spectrum (5–115 Hz). Data less than 5 Hz and from 115 to 125 Hz were not used due to the steep frequency response roll-off at these frequencies.

The acoustic time series at each location was first assessed by decomposing the spectrum by frequency and sound level. Mean spectral levels reported in decibels (dB re 1 μPa^2/Hz) were calculated in three 20-Hz bands (10–30 Hz, 40–60 Hz, and 85–105 Hz) for comparison to the full spectrum (5–115 Hz). The bands were selected to target the dominant frequencies of source types, with the understanding

Table 86.1 Data availability from CTBTO IMS locations from start date to 11 January 2013

Location	Ocean	CTBTO IMS code	Coordinates	Start date	Data gaps (days)
Diego Garcia	Indian	H08	6°34′21″ S, 71°01′43″ E	21 January 2002	40
Ascension Island	Atlantic	H10	7°84′57″ S, 14°48′02″ W	4 November 2004	4
Wake Island	Pacific	H11	19°71′36″ N, 166°89′11″ E	25 April 2007	14

CTBTO Comprehensive Nuclear Test Ban Treaty Organization, *IMS* International Monitoring System

that the full spectrum of any source (i.e., shipping) has the potential to contribute energy to more than one band. The 10- to 30-Hz band reflects contributions from natural seismic activity and from blue whale and fin whale vocalizations (Stafford et al. 2004; Samaran et al. 2010; Gavrilov et al. 2012; Nieurkirk et al. 2012). The 40- to 60-Hz band reflects energy contributions from shipping, animal vocalizations, and seismic air guns, making this a "transitional" band. The 85- to 105-Hz band was selected to target contributions from distant shipping. Mean spectral levels were calculated using a 15,000-point DFT Hann window and no overlap to produce sequential 1-min power-spectrum estimates over the duration of the data-set. Averages were computed using intensity levels and were then converted back to decibel units. Three daily percentile parameters (P1, P50, P99) were identified from 1440 1-min power-spectrum estimates calculated each day. Each daily percentile value represents the level below which a certain percentage of measurements fall within a single day. The P1 value is representative of the sound floor (quietest ambient conditions). The P50 value is the daily median, and the P99 value reflects the most extreme sound levels occurring within a day.

Acoustic trends were assessed using all the data available from the date of inception at each island location to 11 January 2013 (Table 86.1). A linear regression model of sound level with date was fit for each of the time series to explore the long-term trend of the sound level. No inferential conclusions were drawn from the linear regression models due to the non-Gaussian distribution and serial correlation of the data.

3 Results

Decomposing the acoustic time series by frequency and sound level afforded the opportunity to examine details of the ambient sound that would not have been observed with traditional descriptive statistics of the full spectrum. Linear regression analyses on the full-time series at each location showed no consistent trends across ocean basins and trends within an ocean were frequency dependent (Fig. 86.1). In the Indian Ocean at Diego Garcia, there has been a consistent increase in the sound floor (P1), but the P99 levels decreased over the past decade. The P50

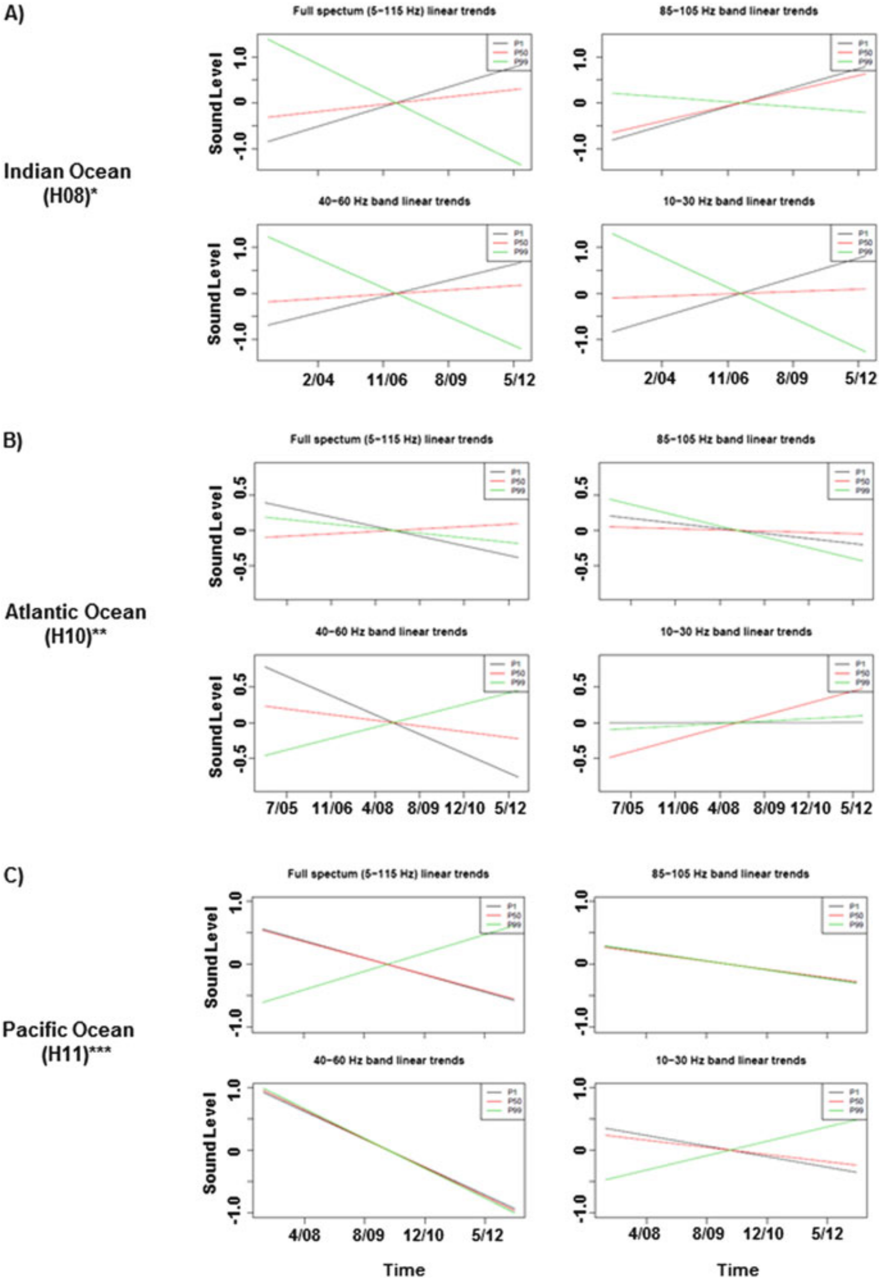

Fig. 86.1 Summary of linear trends for the full spectrum and 20-Hz band analyses from the Indian Ocean (H08N1) at Diego Garcia (**a**), Atlantic Ocean (H10N1) at Ascension Island (**b**), and Pacific Ocean (H11N1) at Wake Island (**c**). P1 is the sound floor, P50 is the median, and P99 is the time series of loudest events. Sound levels are in dB re 1 MPa^2/Hz. *, Trend over a 10-year dataset; **, trend over an 8-year dataset; ***, trend over an ~6-year dataset. From Miksis-Olds (2013)

trend from Diego Garcia showed a strong increase in the 85- to 105-Hz band, whereas the trend minimally increased in the other three frequency categories. In the Atlantic Ocean at Ascension Island, there was an overall decreasing trend for the sound floor in the full spectrum, the 40- to 60-Hz band, and the 85- to 105-Hz band. There was no change in the 10- to 30-Hz sound floor at this location over the past 8 years. The median (P50) levels over the same time period increased 0.5–1 dB in the full spectrum and the 10- to 30-Hz band while remaining approximately the same in the 40- to 60-Hz and 85- to 105-Hz bands. The most extreme levels at Ascension Island showed the greatest difference in the 40- to 60-Hz band level, most likely associated with an increase in air gun activity (Nieurkirk et al. 2012). The extreme sound levels either decreased slightly or remained the same for the other three frequency categories. The Pacific Ocean time series at Wake Island spanned 5.5 years. During this time, there was an overall decrease in sound level for the P1 and P50 sound levels. The exception to this overall trend was no change in the 40- to 60-Hz band for the P50 levels. There was no consistent trend in the P99 levels in the Pacific Ocean at Wake Island. The full spectrum showed the greatest increase, whereas the 40- to 60-Hz band showed the greatest decrease of approximately −1.9 dB.

4 Conclusions

The rise in North Pacific Ocean ambient-sound levels at a rate of 2–3 dB/decade from the 1960s to the early 2000s has sparked concern about the impact of rising sound levels on the marine environment (Ross 1976, 1993; Andrew et al. 2002; McDonald et al. 2006; Chapman and Price 2011), but there has been a lack of detailed studies on ambient-sound trends in other areas for comparison. This work presents trends from regions of the Equatorial Pacific, South Atlantic, and Indian Oceans over the past 5–10 years. Parsing the soundscape into frequency categories and sound-level percentiles allowed for a detailed examination of the acoustic environment that would not have been possible with a single analysis of the full spectrum or with a single sound-level parameter. The use of percentiles was valuable in discriminating between trends in the sound floor, median levels, and loudest sound levels. Analysis of the different sound-level parameters indicated that a single parameter trend analysis is not sufficient for a comprehensive understanding of sound-level dynamics at any one location. Based on the inconsistency of patterns and trends across sound-level parameters and frequency at a single location, it is recommended that the soundscape of any region be decomposed into multiple-frequency and sound-level components to obtain a full understanding of the acoustic dynamics.

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Chapter 87
Pile-Driving Pressure and Particle Velocity at the Seabed: Quantifying Effects on Crustaceans and Groundfish

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Abstract We modeled the effects of pile driving on crustaceans, groundfish, and other animals near the seafloor. Three different waves were investigated, including the compressional wave, shear wave, and interface wave. A finite element (FE) technique was employed in and around the pile, whereas a parabolic equation (PE) code was used to predict propagation at long ranges from the pile. Pressure, particle displacement, and particle velocity are presented as a function of range at the seafloor for a shallow-water environment near Rhode Island. We discuss the potential effects on animals near the seafloor.

Keywords Noise • Ears • Damage • Lobsters • Flounder

1 Introduction

An aspect of the study of the effects of pile driving in the coastal ocean concerns marine life at or just under the seafloor. In the United States, offshore wind farms are being planned and construction could begin in the near future along the east coast of the United States. Some of the sites being considered are known to be habitats for crustaceans such as the American lobster, *Homarus americanus*, which has a range from New Jersey to Labrador along the coast of North America. Groundfish such as summer flounder, *Paralichthys dentatus*, and winter flounder, *Pseudopleuronectes americanus*, also are common along the east coast of the United States (Nelson 1994). Besides sharing the seafloor in locations where wind farms are planned, all three of these species are valuable commercially.

Pile driving is required for the installation of offshore wind turbines in water depths as deep as 30 m. The wind farms planned for Rhode Island waters will predominantly use a lattice-jacket type of structure requiring piles with a diameter of 1.2 m to be

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driven in water depths of ~25 m. The piles will be driven ~60 m into the seafloor. It is estimated that each pile will be require 10,000 strikes/pile for 40,000 strikes/substructure. During construction, there may be a possibility of affecting sea life near the pile driving. We concentrate here on the sea bottom. Hazelwood and Macey (2013) also studied the potential effects of pile driving on sea life with measurements and modeling, with an emphasis on the interface wave. Reinhall and Dahl (2010, 2011) measured and modeled the in-water Mach wave emanating from the struck pile. There is little published work on the effects of pile driving on lobster or flounder. But there is related literature that bears on this topic. Payne et al. (2007) reported on the effects of air gun noise on the American lobster. Christian et al. (2003) studied the effects of seismic exploration on the snow crab. Casper et al. (2012) and Halvorsen et al. (2012) investigated the effects of pile-driving sound on Chinook salmon.

2 Pile-Driving Impact Wave Description Near the Seafloor

During impact pile driving, a hammer hits the pile head and energy is transferred into the pile by the impulse created by this impact (Massarsch and Fellenius 2008). As the hammer strikes the pile, a compressional body wave is generated within the pile. The wave travels down the pile to the toe where part of the wave energy is reflected within the pile and part is transmitted to the soil. In addition, on its way down and back up the pile, the wave interacts with the shaft friction and energy is transmitted into the soil. The energy induced at the pile head is principally divided into energy used for penetration of the pile, energy reflected back up the pile, and energy transmitted into the soil.

At the pile toe, the displacement of soil generates both compressional P-waves and shear S-waves that propagate outward from the tip in a spherical waveform in all directions. The skin resistance of the pile leads to the generation of a conical wave front of vertically polarized body shear waves expanding from the shaft. The angle of the cone is quite shallow because the velocity of the driving impulse traveling down the pile at the compression wave velocity is usually much higher (ten times or more) than the shear wave velocity in the soil. As the P- and S-waves hit the ground surface, some energy is converted into interface or surface waves (Scholte waves in the case of water-sediment interface) while some energy is reflected back into the sediment. In summary, compressional, shear, and interface waves are created due to the impact pile-driving operation.

2.1 Compressional Waves

Compressional waves are also known as primary, longitudinal, or P-waves. P-waves are linked to a volume change in the medium because they involve successive compression and rarefaction (dilatational wave). Particle motion is parallel to the direction of wave propagation. P-waves can travel through both solids and fluids. The P-wave (or primary wave) involves no shearing or rotation of the material as it passes through the medium. P-waves are the fastest wave present in a solid material. In terms of the elasticity modulus (E), bulk modulus (K), density (ρ), and Poisson's ratio (ν), the P-wave velocity (c_p) can be written (for an elastic medium) as

$$c_p = \sqrt{\frac{E(1-\nu)}{\rho(1-2\nu)(1+\nu)}} \tag{87.1}$$

2.2 Shear Waves

Shear waves are also known as secondary, transverse, or S-waves. An S-wave causes shearing deformations as it propagates through a medium. S-waves cannot travel through fluids because fluids have no shearing stiffness. In terms of the shear modulus (G) and density (ρ), the shear wave velocity (c_s) can be written as

$$c_s = \sqrt{\frac{G}{\rho}} \tag{87. 2}$$

S-waves are often divided into two perpendicular components, SH-waves and SV-waves. SH-waves are S-waves in which the particles oscillate in a horizontal plane. SV-waves are S-waves in which the particles oscillate in a vertical plane. Any given S-wave can be expressed as the vector sum of the SH and SV components.

2.3 Interface Waves

The Scholte wave is an interface wave that propagates along the water-sediment interface, decaying exponentially in amplitude away from the boundary in both water and sediment. Shear properties of the near-surface sediments are perhaps most readily determined from the propagation characteristics of Scholte waves. The propagation speed and attenuation of the Scholte wave are closely related to shear-wave speed and attenuation over a depth of 1–2 wavelengths into the seabed but are relatively insensitive to the compressional-wave properties (Dosso and Brooke 1995). As mentioned previously, when the P- and S-waves are incident on the ground surface, some energy is converted into interface or surface waves. Massarsch and Fellenius (2008) introduced a distance, called the critical distance (r_crit), for pile driving on land, which is the distance from the pile to where a spherical wave (P-wave) emitted from the pile toe refracts as a surface wave when reaching the ground surface. The r_crit from the pile, where wave refraction will occur at the ground surface, can now be determined using

$$r_{crit} = \tan\theta_{crit} d \tag{87. 3}$$

The angle θ_{crit} is defined as follows

$$\theta_{\mathrm{crit}} = \arcsin\left(\frac{c_s}{c_p}\right) \tag{87. 4}$$

where c_{s} and c_{p} are the shear and compressional wave speeds, respectively, and d is the depth of penetration of the pile.

Based on Eqs. (87.3) and (87.4), generation of the interface wave can be expected at some distance (based on the medium properties and pile penetration) from the pile. Even though measurement and modeling of the interface wave (Scholte wave) is a standard technique for estimating shear speed in the bottom (Potty and Miller 2012), it has not been investigated extensively in the context of offshore pile driving. In a recent study by Hazelwood and Macey (2013), ground roll waves (interface waves) with frequencies around 20 Hz have been measured and modeled using transient finite element (FE) analysis. We investigated the presence of body (compressional and shear) and interface (Scholte) wave types in this study using the FE method and parabolic equation (PE) modeling. The modeling approach is briefly outlined in Section 3.

3 FE and PE Modeling of the Pile-Driving Signal

To simulate offshore impact pile-driving noise, a commercial FE code (Abaqus 6.11) and a standard underwater acoustic propagation model (Monterey-Miami PE [MMPE] model) were used. We used the FE code to model the harmonic response of the pile to calculate the acoustic pressure amplitude on the surface of the pile due to impact loading. The MMPE model is then used to predict long-range noise propagation from the offshore pile location. The complex acoustic pressure amplitudes on the surface of the pile produced by the steady-state dynamic analysis option available in the FE model were used as a starting field at corresponding frequencies for the MMPE propagation model. We verified the FE model results by comparing results from Stephen (2005) and Stadler and Woodbury (2009) with the measured data from Reinhall and Dahl (2011).

In the FE model analysis, an axisymmetric model was used, assuming no variation along the azimuthal angle in the cylindrical coordinate system for a shallow-water environment. Our axisymmetric model considers 26 m of water and 20.8 m of sediment. The length and radius of the pile are 46.8 and 1.8 m, respectively, in this model. (The latest design for piles planned for the Rhode Island wind farm are 1.2 m in diameter and will be driven 60 m into the sediment.) To provide a starting field for the MMPE model, we output the pressure field on the outer surface of the pile in contact with water and sediment acoustic media. Elastic properties such as Young's modulus and Poisson's ratio were input parameters to the FE model that were used to characterize the steel pile. The density (ρ) and bulk modulus (K) defined the acoustic media with a corresponding speed of sound given by $c = \sqrt{(K/\rho)}$. The specific values of the material properties used in the analysis are shown in Table 87.1.

Table 87.1 Material properties for the finite element model

Parameter	Water	Bottom	Steel
Density ($\rho, kg/m^3$)	1,025	1,200	7,900
Bulk Modulus (K, GPa)	2.306	2.995	–
Young's Modulus (Y, GPa)	–	–	200
Poisson's Ratio (ν)	–	–	0.3

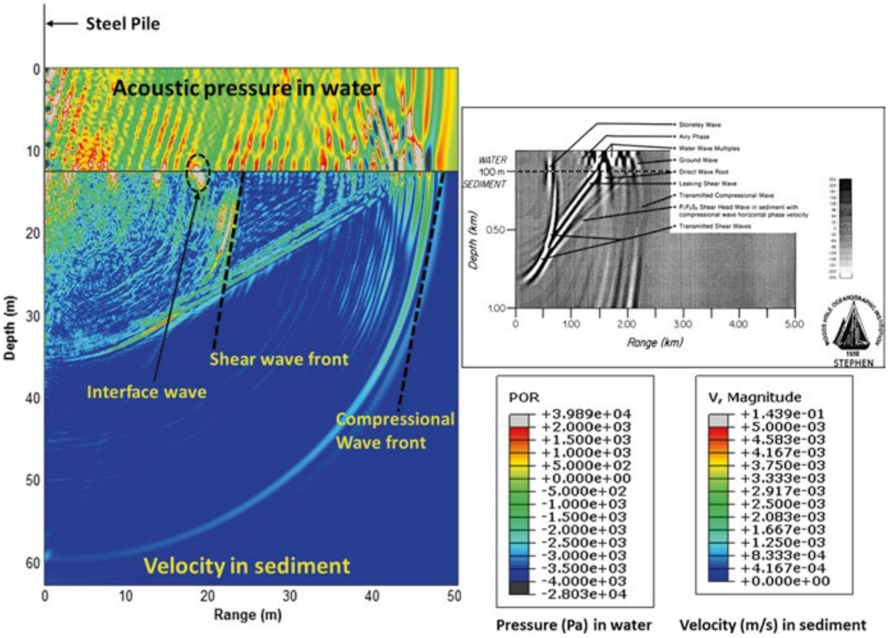

Fig. 87.1 *Left*: acoustic pressure in the water column (0–26 m depth) and particle velocity at the bottom to a range of 50 m. *Right*: comparison to the finite difference modeling of Stephen (2005)

Mesh size requirements dictated that at least six elements should exist within the shortest wavelength (corresponding to the highest frequency) of interest. For this study, we were most interested in the radiated acoustic energy between 100 and 1,024 Hz for incorporation into the MMPE model. To avoid reflection from the geometrical boundary of the acoustic media in the FE model, a nonreflecting boundary condition (available in Abaqus 6.11) was applied. Before we coupled the harmonic acoustic pressure response on the pile to the MMPE propagation model's starting field, we verified the evolution of the acoustic waves with time and their propagation in water and sediment. This was accomplished by using the implicit dynamic analysis option available in Abaqus 6.11 with the pressure impact loading applied on top of the pile. The equation for pressure impact loading was derived by Reinhall and Dahl (2011). An example of the FE output is shown in Fig. 87.1, and it is compared to the finite difference modeling done by Stephen (2005).

3.1 Oceanographic and Geological Environment near Block Island, Rhode Island

There is a proposal to install and operate five 6-MW Siemens Direct Drive turbines, supported by lattice-jacket structures, south of Block Island in Rhode Island state waters in the near future. The water depth in the region is ~30 m. A field test was conducted at this location in October 2009 during which acoustic data were collected on a stationary receiver using a 200-Hz J-15 source deployed from a drifting ship. This provided acoustic data as a function of range that were compared to model predictions. The present study used some of the data and results from the 2009 field study. During the transmission loss (TL) field test, measurements of temperature and salinity were made using a conductivity, temperature, and depth (CTD) sensor, which was then used to calculate the sound speed. The sound speed showed a slightly downward refracting profile with a sound speed of 1,520 m/s in the 10-m-thick surface mixed layer. It reduced to 1,515 m/s below 15 m depth. The bottom was assumed to consist of a sediment layer and a basement. The sediment parameters and the thickness of the sediment layer were estimated using a simple iterative inversion by matching the modeled and measured TL. The compressional wave speed in the sediment layer and basement were estimated as 1,590 and 1,770 m/s, respectively. The thickness of the sediment layer inversion using the approach based on TL comparison was 15 m. These ocean sound speed measurements and sediment geoacoustic inversions provided the input data for the model calculations performed in the present study.

3.2 Results of Modeling

A compressional wave in the pile caused by the impact pressure loading produces an associated radial displacement motion due to the Poisson effect. The radial displacement propagates downward. Because the speed of sound in the steel pile is higher than that in water, the rapidly downward propagating wave produces an acoustic field in the shape of an axisymmetric cone. The cone's apex travels concurrently with the pile deformation wave front. When the wave front reaches the pile's terminal end, it is reflected upward.

The acoustic field produced by the impact loading on the pile in the near field is calculated using the FE method. This pressure field is then used as the starting field for MMPE, which then can be propagated efficiently in range. For conventional applications (such as a point source or line array), the starting field for the MMPE model can be easily defined in the input file. However, the pressure field generated from pile driving is more complicated in terms of its vertical distribution and its frequency dependence. We employed the steady-state dynamic analysis that allowed us to specify input loading as impact pressure as a function of frequency. Our loading condition was calculated by taking the discrete Fourier transform of the time-dependent approximation for impact pressure as specified by Reinhall and Dahl (2011). To adequately model the frequency dependence of the complex pressure in the water and bottom, 184 nodes were defined along a vertical line on the surface of the pile. Each node supplies a complex acoustic pressure between 0.5 and 1,024 Hz with a 0.5-Hz sampling, generating a 2,048 × 184 frequency-dependent complex pressure field matrix. Thus, a frequency-specific vertical starting field can be obtained by extracting the pressure at the desired frequency.

The MMPE model accepts the complex pressure starting field at a given frequency of interest as an initial value problem in depth and propagates the solution in two acoustic regimens (water and sediment). One of the major environmental input files, the sound speed profile (SSP) used for this study was measured during a previous field study, and the bottom and deep-bottom property including density and compressional wave speed also came from inversions carried out using data from the same field study. Details of this field study were discussed in Section 3.1. We considered range-independent bathymetry along a track and modeled the propagation along this track to a range of 3 km. The water depth along this path was assumed to be 26 m. The objective of the present study was to predict the acoustic pressure and vertical component of the particle velocity along the water-sediment interface.

The MMPE model was run at multiple frequencies to calculate broadband complex acoustic pressure at the interface as function of range in the frequency band of 100 to ~1,024 Hz. An inverse fast Fourier transform (IFFT) of the frequency-dependent complex acoustic pressure at different ranges produced the acoustic pressure in the time domain. The peak sound pressure level (peak SPL; in dB re 1 μPa) can be then calculated in the time domain as a function of range. In addition, the MMPE model also provides vertical and horizontal components of particle velocity in the entire numerical domain. To investigate the effect of particle velocity on the animals living on the ocean bottom, we calculated the vertical component of the particle velocity from the MMPE model. The IFFT of the vertical component of the complex particle velocity in the frequency band was used to get the peak vertical velocity in the time domain as a function of range. The peak SPL was magnitudes higher than 220 dB re 1 μPa within the range of 20 m, which is comparable to the measured data of Reinhall and Dahl (2011). The SPL is greater than 170 dB re 1 μPa at 3,000 m. The vertical component of the particle velocity is close to 0.05–0.1 m/s within the range of 5 m and remains greater than 0.005 m/s at 150 m from the piling location.

4 Sensitivity of Benthic Animals to Pile Driving

4.1 Lobsters

Payne et al. (2007) found that exposure of lobsters to seismic air gun signals with a peak-to-peak SPL of 202 dB re 1 μPa had no apparent effects but did observe some sublethal effects such as feeding and serum biochemistry. Assuming a signal symmetrical waveform, this exposure corresponds to a peak SPL of 196 dB re 1 μPa.

This level could be reached at the seafloor at a range of 500 m based on our modeling. Particle velocity and pressure are proportional for a plane acoustic wave in an infinite, isotropic medium. However, near a boundary like the seafloor, the relationship is more completed. Our modeling predicts that the vertical acoustic particle velocity at the seafloor will be ~10 cm/s near the pile, above ~1 cm/s out to 150 m, and above 0.1 cm/s out to 400 m. The effect of this vertical velocity on lobsters is not known.

4.2 Flounder

Flounder adults do not have swim bladders (Nelson 1994), and so a single-strike level (peak SPL) of 206 dB re 1 μPa proposed for fish (Stadler and Woodbury 2009) will likely be conservative. Halvorsen et al. (2012) proposed a response weighted index (RWI) for Chinook salmon, a fish with a swim bladder. Because no work has been published on the effects of pile driving on flounder, we applied the RWI salmon paradigm to that species. We expect that the predictions made will be conservative. The RWI ranges from 1 (mild trauma) to 3 (moderate injury) to 5 (mortal injury, dead within an hour) and higher. The RWI is related to the cumulative sound energy level (SEL_{cum}) and the number of strikes ($N_{strikes}$) as (Halvorsen et al. 2011)

$$RWI = \exp\left(-30.050 + 0.149 * SEL_{cum} - 0.000171 * N_{strikes}\right) - 1 \qquad (87.5)$$

In Fig. 87.2, the RWI is shown assuming 960 and 1,920 pile strikes. These quantities were used in the Halvorsen et al. (2012) work. Because the piles planned off Rhode Island will be struck 10,000 times/pile, Halvorsen et al. used 960 and 1,920 strikes

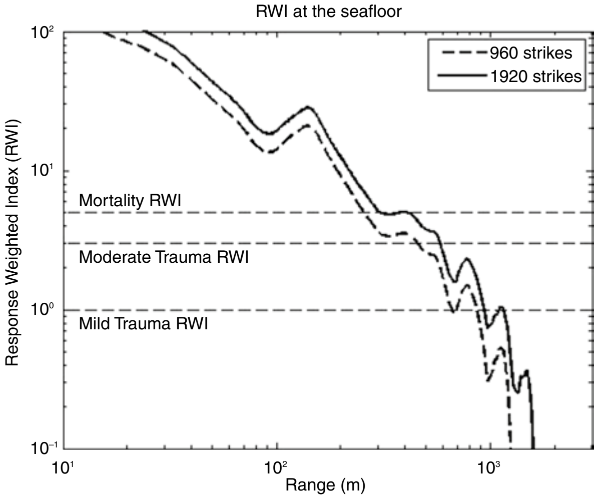

Fig. 87.2 Response weighted index (RWI) predicted as a function of range from the pile installation for 960 and 1,920 pile strikes. Mortality, RWI of 5; moderate trauma, RWI of 3; mild trauma, RWI of 1 as suggested by Halvorsen et al. (2012)

and the animals likely left the immediate area of the pile, the number of pile strikes to use in Eq. (87.5) is a question. Without any other information, we decided to use the Halvorsen et al. numbers and assumed that the ranges were conservative. Although not shown, the seafloor RWI is higher than the in-water RWI at most ranges. The range to the mortality RWI is ~250 m at the seafloor for 960 pile strikes. The effects of the peak particle velocity estimated from the modeling as mentioned in Section 4.2 on flounder are not known.

5 Conclusions

We modeled the effects of pile driving on American lobsters, winter flounder, and summer flounder near the seafloor. Three different waves were investigated, including the compressional wave, shear wave, and interface wave. A FE technique was employed in and around the pile while a PE code is used to predict propagation at long ranges from the pile. Pressure, particle displacement, and particle velocity were calculated as a function of range at the seafloor for a shallow-water environment near Rhode Island. For lobsters, there may be effects out to 500 m from the pile driving for a single strike. Using a very conservative criterion proposed for fish that have a swim bladder, the effects are limited to 250 m from the pile driving for 960 strikes.

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Chapter 88
Measuring Hearing in Wild Beluga Whales

T. Aran Mooney, Manuel Castellote, Lori Quakenbush, Roderick Hobbs, Caroline Goertz, and Eric Gaglione

Abstract We measured the hearing abilities of seven wild beluga whales (*Delphinapterus leucas*) during a collection-and-release experiment in Bristol Bay, AK. Here we summarize the methods and initial data from one animal and discuss the implications of this experiment. Audiograms were collected from 4 to 150 kHz. The animal with the lowest threshold heard best at 80 kHz and demonstrated overall good hearing from 22 to 110 kHz. The robustness of the methodology and data suggest that the auditory evoked potential audiograms can be incorporated into future collection-and-release health assessments. Such methods may provide high-quality results for multiple animals, facilitating population-level audiograms and hearing measures in new species.

Keywords Anthropogenic noise • Sensory • Marine mammal • Cetacean • Odontocete • Arctic

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1 Introduction

Hearing is the primary sensory modality for odontocete marine mammals. They are generally considered to have sensitive hearing and may detect a broad range of frequencies. Relying on hearing can be particularly adaptive in the marine environment where light and other cues are often limited and natural sounds are frequently abundant. Yet these sensitive auditory abilities may also be easily impacted by anthropogenic noise.

Human use of the Earth's oceans has steadily increased over the last century, resulting in an increase in anthropogenically produced noise (e.g., National Academy of Sciences 2003). The Arctic is no exception to this increase (Blackwell and Greene Jr 2003). Reductions in polar sea ice and the opening of the Northwest Passage presumably will open up habitats for many top predators. Yet this decrease in sea ice provides greater human access to a high-latitude environment, and such a change is poised to transform a relatively pristine environment into one saturated with human activities and associated noise. Sources are varied and include naval exercises, boundary definitions, shipping/movement along Alaska's North Slope, seismic resources exploration, and the construction of an infrastructure needed to support it (Wang and Overland 2009; Titley and St. John 2010). These changes encompass the habitats of *Delphinapterus leucas* (beluga whales) and other top predators. Despite this obvious overlap of human-natural interests, there is a poor understanding of influences of these sound-associated changes. To estimate the impacts of this noise, it is crucial to evaluate the natural hearing abilities and the variation with marine mammal populations.

Yet a primary challenge is that audiograms of odontocete marine mammals have most often been estimated from stranded animals or nonwild individuals (for a review, see Mooney et al. 2012). In many instances, these records have produced valuable data that are otherwise unavailable. For example, hearing in several stranded beaked whale species have helped define what these sound-sensitive animals hear (Finneran et al. 2009; Pacini et al. 2011). The audiogram of a stranded infant Risso's dolphin helped redefine what the species actually detects (Nachtigall et al. 2005). Work with trained odontocetes provides scientific data that are likely unique to those settings and can address how animals hear or how they may be protected from anthropogenic noise (Nachtigall and Supin 2008). Yet, in many instances, health-compromised stranded animals may not have normal auditory abilities and thus are not necessarily representative of wild populations. Furthermore, without baselines for wild individuals, it is difficult to put differences and results of nonwild individuals in a relative context. Clearly, there is value in increasing the number of animals within a species measured for hearing capabilities whenever possible.

Here we describe the methods and initial results for measuring the hearing of wild *D. leucas* (Castellote et al. 2014). The goal of this study was to determine hearing sensitivity in wild Bristol Bay *D. leucas* during a planned collection-and-release operation. Monitoring of *D. leucas* has been recommended in recent years because this species is likely to be negatively impacted by climate change and because such a broadly dispersed, high-trophic feeder can serve as an effective sentinel of the ecosystem(s) in which it lives (Moore 2008; Moore and Huntington 2008; Simpkins et al. 2009). Because noise may impact *D. leucas* in a variety of ways, it is essential to determine what these animals hear.

In view of the expected changes in the Arctic acoustic environment, expanding our knowledge of *D. leucas* hearing is of central importance for an appropriate conservation management framework. One of the five distinct stocks of *D. leucas* whales that are currently recognized in US waters, the Cook Inlet *D. leucas* population is endangered and efforts for its recovery to date have not been successful. The impact of anthropogenic noise has been identified as a serious threat, potentially impeding recovery (NMFS 2008). On the contrary, the Bristol Bay *D. leucas* population is increasing and is considered to be a healthy population (NMFS 2008). The acoustic environment in Bristol Bay is different; many of the chronic anthropogenic sources typically found in the Cook Inlet *D. leucas* habitat are essentially absent or seasonally present at lower intensities in the Bristol Bay habitat. This suggests that Bristol Bay *D. leucas* are a valuable asset to evaluate baseline hearing and health measures for comparison to affected populations such as Cook Inlet *D. leucas*.

2 Temporary Collection of Beluga Whales and Hearing Test Methods

This study was conducted in September 2012 in Bristol Bay, AK. The audiograms were measured during an overall health assessment study that required the collection and release of *D. leucas*. Audiograms were obtained from seven of seven belugas tested. The procedures were similar to those followed by Ferrero et al. (2000) and were conducted under National Marine Fisheries Service Marine Mammal Research Permit No. 14245 and approved by the necessary Institutional Animal Care and Use Committees. The full results are published elsewhere (Castellote et al. 2014); here we provide a summary of the methods and preliminary results.

Bristol Bay is a generally shallow, muddy-bottomed estuary system that supports a population of *D. leucas*. Using three 3.5-m aluminum skiffs and one soft-bodied inflatable boat, we searched for an adult beluga. When a suitable animal was spotted (Fig. 88.1), one of the skiffs would follow and gradually approach the whale to encourage it to swim into shallow water (<2 m). From one of the boats, a 125-m-long by 4-m-deep net made of 0.3-m braided square mesh was deployed around the whale. Once the deployment boat and net encircled the whale, the inflatable boat approached the outside of the net and three handlers placed a soft tail rope around the whale's peduncle. The rope's other end was fixed to the inflatable boat to secure the whale. The large net was gradually recalled while a "belly-band" stretcher was placed under the *D. leucas*. Handholds in this stretcher facilitated adjusting the whale's position as the water depth changed with the tide. The animal was then positioned parallel to the small inflatable boat. The *D. leucas*'s head typically rested on or was just above the soft mud bottom, keeping the lower jaw and primary hearing pathways below the water surface. The animal's blowhole was generally above the surface. This setup

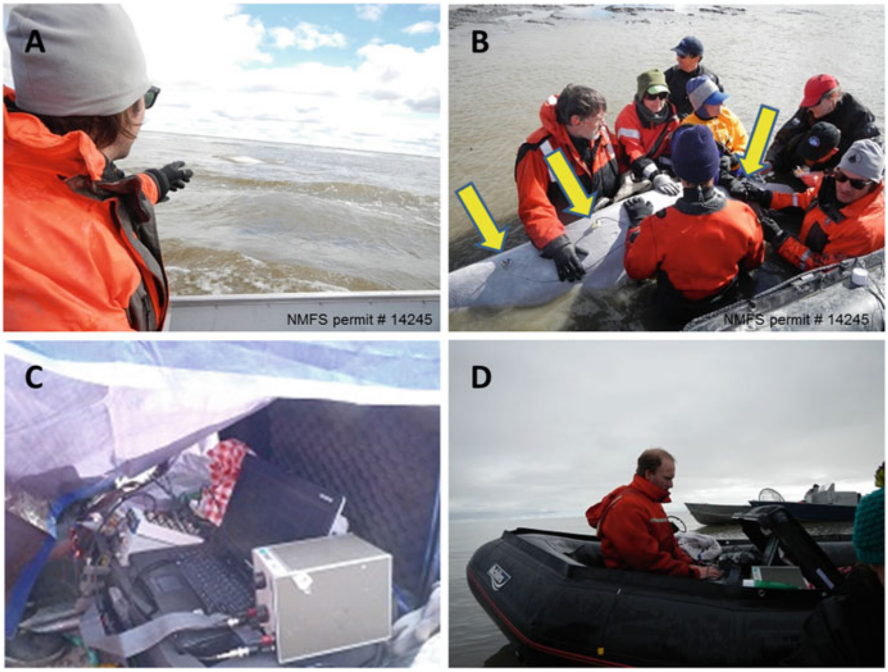

Fig. 88.1 (**a**) Spotting a *Delphinapterus leucas* from the aluminum skiff. (**b**) Auditory evoked potential (AEP) audiogram setup. *Arrows*, recording, reference, and ground electrodes from posterior to anterior (*right* to *left*). A measure of breath is also being taken concurrently. (**c**) AEP system in its case. (**d**) AEP system in the soft inflatable boat during data recording

was consistent for all animals, except one for which the water level was too low and this test was conducted partly out of the water. Animals were maintained in this position for the audiogram and health exam. The auditory evoked potential test equipment was outfitted in a ruggedized case; both it and the operator sat in the small inflatable boat beside the *D. leucas* during the hearing tests (Fig. 88.1).

Hearing was tested using auditory evoked potential methodology following methods generally described elsewhere (e.g., Nachtigall et al. 2007). Sound stimuli, generated in a custom program, consisted of amplitude-modulated tone-pip stimuli, 20 ms in duration, and presented at a modulation rate of 1 kHz and 20 s^{-1}. Tones were presented through a suction-cup transducer attached to the tip of the lower jaw. Evoked potential data were recorded for 30 ms, starting concurrently with tone stimuli. Responses were bandpass filtered from 300 to 3,000 Hz. Five hundred sweeps were averaged per single record by the custom program and stored on a semirugged laptop computer. Thresholds were determined taking the fast Fourier transform-based frequency spectra of each envelope following responses (EFRs), and plotting those microvolt peaks relative to their respective sound pressure. A best-fit regression line was fit to these peak data points. A sound level value where the regression line theoretically generated a 0-μV response was taken as the threshold for that frequency.

3 Results and Discussion

Audiograms were successfully collected from all seven adult *D. leucas* whales temporarily collected and tested. Evoked response waveforms and EFRs were generally easily identifiable and distinct from the background electrophysiological noise. The inset in Fig. 88.2 shows an EFR that was recorded using stimuli of ~20 dB around the hearing threshold of 32 kHz. Such a measurement would take ~30 s to collect. Thus, overall thresholds at a particular frequency were obtained in 3–5 min. This relatively rapid threshold measurement facilitated collecting multiple thresholds per animal but also minimizing the "with-animal" time. For example, the audiogram of animal 7 consisted of 12 frequencies tested. Two of these (4 and 150 kHz) did not induce measureable AEPs. The entire dataset was collected in 55 min, which included multiple breaks for other measurements such as obtaining blood samples or repositioning the animal. Records were collected in concert with a suite of other measurements, with no discernible impact on the physiological noise. This allowed for a relatively efficient data collection when compared with behavioral methods that require significant time to train animals and conduct experiments. It is also relatively quick for other AEP audiograms that make take multiple days (sessions). Here we collected seven audiograms over 6 field days (including 1 day with poor weather conditions when no whales were sighted).

Despite the potential challenges of the experiment (cold conditions, electrophysiology close to the water, confined spaces, concurrent measurements potentially introducing noise, and the safety and welfare of the people and animals), the audiograms were of very good quality. They are of equal quality to the field-based collection-release audiometric data of Cook et al. (2004) for bottlenose dolphins (*Tursiops truncates*) and of Nachtigall et al. (2008; see also Mooney et al. 2009) for white-beaked dolphins (*Lagenorhynchus albirostris*) Our success both in the ease and safety of data acquisition and the quality of the data suggests that the methods could easily be applied to other species in similar situations. This is of particular

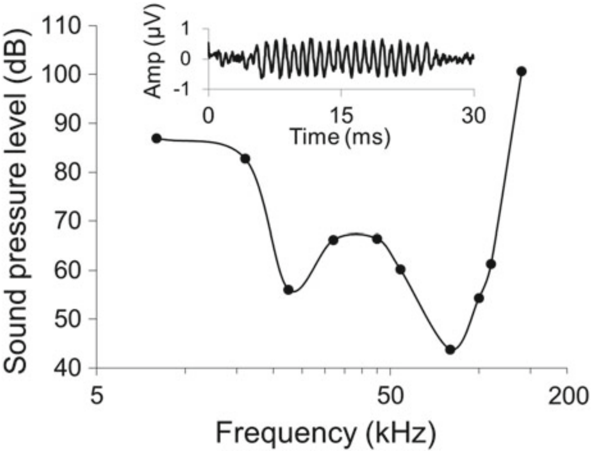

Fig. 88.2 AEP audiogram and waveform (*inset*) of *D. leucas* No. 7. This animal had the overall mean lowest threshold

importance for populations where anthropogenic noise is chronic and has been identified as a potential stressor. Examples are the endangered Cook Inlet *D. leucas* or the threatened St. Lawrence *D. leucas* populations. The prevalence of anthropogenic noise in their habitat and its cumulative effects might be compromising the survival of both *D. leucas* populations (NMFS 2008; DFO 2012). This assertion is based on current knowledge of the level and acuity of anthropogenic noise in these ecosystems (e.g., Gervaise et al. 2012) and our understanding of *D. leucas* hearing and acoustic communication. However, because of the inherent difficulties in evaluating the noise impact on cetaceans, there are no data supporting this hypothesis. Audiograms using the method described here could be collected in the Cook Inlet and in the St. Lawrence Estuary to measure the hearing of *D. leucas* with greater exposure to anthropogenic noise and could then be compared with the baseline audiogram for Bristol Bay *D. leucas*.

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Chapter 89

Auditory Discrimination of Natural and High-Pass Filtered Bark Vocalizations in a California Sea Lion (*Zalophus californianus*)

Jason Mulsow and James J. Finneran

Abstract A California sea lion performed a psychophysical auditory discrimination task with a set of six stimuli: three barks recorded from conspecific males and high-pass filtered versions of the barks that removed the majority of energy at fundamental frequencies. Discrimination performance and subject reaction times (RTs) suggested that the vocalizations were all perceived as fairly dissimilar. This preliminary study hints that low-frequency components are a salient part of the California sea lion bark despite elevation of this species' aerial hearing thresholds and the potential for elevated environmental noise levels at frequencies below 1 kHz.

Keywords Pinniped • Hearing

1 Introduction

California sea lions are a highly vocal species. Aerial vocalizations are used in social interactions in crowded coastal rookeries, including those between competing males and between mothers and pups during reunions (Schusterman 1978; Insley et al. 2003). The importance of these vocalizations in California sea lion behavior is also highlighted by the fact that this species possesses sensitive aerial hearing despite adaptations of the ear for underwater function (Repenning 1972; Reichmuth et al. 2013). The frequency range of best aerial hearing sensitivity in the

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California sea lion is roughly 8–20 kHz; however, this does not correspond with many prominent lower frequency components in their vocalizations. This is demonstrated by the male bark vocalization, a harmonic signal with fundamental frequencies that are commonly below 1 kHz (Peterson and Bartholomew 1969). The perceptual relevance of these lower frequency components in processes such as the acoustic discrimination of individuals is therefore of interest. Investigation of the perception of low-frequency components is additionally of interest when considered in terms of the potential effects of noise because anthropogenic and natural noise in coastal environments may interfere with communication (Richardson et al. 1995; Southall et al. 2007).

In this preliminary study, we conducted a psychophysical discrimination task with a young male California sea lion. Stimuli comprised bark vocalizations recorded from male California sea lions and high-pass filtered counterparts in which the fundamental frequency had been removed. The subject's discrimination performance and RTs were quantified for each stimulus condition and interpreted as a measure of perceptual similarity (Okanoya and Dooling 1988). We hypothesized that the sea lion would be able to accurately discriminate between and have relatively short RTs when discriminating between barks originating from different individuals. Furthermore, we hypothesized that performance would be poor and RTs relatively long for conditions including an unmodified bark and its high-pass filtered counterpart, given the elevated hearing sensitivity of this species at low frequencies.

2 Methods

2.1 Subject and General Methods

The subject was a 3-year-old California sea lion (identified as JFN) housed in ocean pens and adjacent haul-out areas at the Navy Marine Mammal Program (San Diego, CA). This sea lion had previously participated in hearing studies, including tonal detection tasks and an amplitude discrimination task with pure tones (Mulsow and Finneran 2011; Mulsow et al. 2011, 2012). The present experimental task was similar to that used during the previous pure-tone discrimination study based on an alternating sound paradigm where the sea lion was trained to provide a conditioned response on detecting a change from background acoustic conditions (e.g., Okanoya and Dooling 1988).

2.2 Stimuli

The acoustic stimuli were three "natural" bark vocalizations (denoted V1, V2, and V3) recorded from three male California sea lions at Año Nuevo Island in July 2009 and 2011 and high-pass filtered versions of these barks in which the fundamental frequency was removed (denoted V1HP, V2HP, and V3HP). The particular barks used in the experiment were chosen because they were recorded while a male oriented toward the recording microphone was vocalizing, the ambient noise coincident with the bark was relatively low, and they had acoustic characteristics that were representative of California sea lion barks (see Peterson and Bartholomew 1969).

Background noise was initially removed from the three barks (V1, V2, and V3) using the noise removal function provided by Audacity sound-editing software (http://audacity.sourceforge.net). After noise removal, these three barks were high-pass filtered at 200 Hz using a zero-phase-shift filter in a custom LabVIEW (National Instruments Corporation, Austin, TX) virtual instrument. The 200-Hz high-pass filter removed any residual low-frequency background noise while maintaining the full-frequency content of each of the barks. High-pass filtered versions of the barks (V1HP, V2HP, and V3HP) were created by removing the fundamental frequencies using the LabVIEW virtual instrument. Finally, all the barks were modified using a fast Fourier transform (FFT) filter (Cool Edit Pro 2.0, Syntrillium Software Corporation, Phoenix, AZ) to account for the frequency response of the Sennheiser HDA200 headphones (Sennheiser Electronic Corporation, Old Lyme, CT) used to present the stimuli.

For behavioral testing, the barks were set to a peak sound pressure level (SPL) of 85 dB re 20 μPa (root-mean-square SPLs of 72–74 dB re 20 μPa). To further prevent the sea lion from using small amplitude differences to discriminate between barks, the levels of the barks were randomly "roved" over a 6-dB range (±3 dB) on each successive presentation (see Section 2.3).

2.3 Experimental Procedure

The experiment took place inside a sound-attenuating hut that was located on floating docks near the sea lion's ocean pen. All of the doors and windows to the room were closed before the beginning of experimental sessions, and activity was kept to a minimum outside the room to reduce interfering noise. A station equipped with a switch to measure RT and a response paddle were attached to a PVC frame in the center of the room. A light that was used to delineate trial periods and a loudspeaker used to indicate correct responses were placed in front of the station and response paddle. The experimenter initiated trials from a control room that was separate from the sound-attenuating hut. Two trainers, who were blind to experimental conditions, remained in front of the sea lion to deliver fish reinforcement and place the HDA200 headphones used for stimulus presentation.

After the sea lion's muzzle was stationed on the latency switch, the headphones were placed over the sea lion's ears, and a trial was initiated from the control room. During the initial part of each trial, the light was turned on and the sea lion was presented with the background vocalization at a rate of 2/s. This background period lasted for a random duration between 0.5 and 3 s. For the first type of trial used in the experiment (a change trial), this background period was followed by a period where the background vocalization alternated with a different target vocalization. The alternation period lasted for 3 s (i.e., six alternations between the target and background vocalizations). The control trials were identical to the change trials except that the background vocalization was presented for the entire trial. The correct answers (i.e., providing a paddle press during the alternation phase of a change trial or remaining on the latency switch on a control trial) were indicated with a "buzz" sound played from a speaker in front of the sea lion followed by fish reinforcement from the trainers. No reinforcement or punishment was given for incorrect responses (i.e., remaining on station on change trials or pressing the paddle on control trials or during the background phase). For each session, the background vocalization was held constant and the target vocalizations comprised the five other vocalizations included in the experiment. Sessions were repeated such that each of the six stimuli acted as the background.

3 Results

Data were collected for 18 sessions; each of the six stimuli acted as the background three times. For all specific vocalization comparisons (e.g., V1 background/V2HP target and vice versa), the sea lion's performance was between 88 and 100%. False alarm (FA) rates within an individual session were 24–27% for three sessions early in data collection but were 14% or less for all other sessions. The pooled FA rate for all control trials in the experiment was 10%.

Median RTs were between 215 and 270 ms for all discrimination conditions. For further analysis, all RTs were pooled based on one of four groupings (same male natural/high-pass, different males natural/natural, different males high-pass/high-pass, and different males natural/high-pass). Median latency was the longest for the same male natural/high-pass condition at 248 ms, shortest for the different males natural/high-pass at 226 ms, and in between for the different males natural/natural and high-pass/high-pass at 234 and 233 ms, respectively.

4 Discussion

The level rove procedure used in this preliminary study allowed for signal amplitude to be ruled out as a factor in JFN's discrimination of the various stimuli. If JFN were using differences in amplitude as the main cue, a high FA rate on control trials and during the prechange period would likely have been observed. The low FA rate compared with discrimination performance indicates that the frequency-related aspects of the barks are probably sufficient for the discrimination of barks produced by different male California sea lions and between the natural and high-pass filtered versions of barks from the same individual. These results are supported by previous field playback studies with male Australian sea lions (*Neophoca cinerea*), which have shown differential behavioral responses to vocalizations produced by different males (Attard et al. 2010), and to frequency-shifted vocalizations from one individual (Charrier et al. 2011).

The ease in discriminating the natural vocalizations from their respective high-pass filtered counterparts suggests that the low-frequency components of the vocalizations are salient to conspecific listeners. Low-frequency components of male California sea lion barks may therefore be an important part of vocal perception despite the relative elevation of hearing thresholds and environmental noise levels at these frequencies. However, preliminary analysis of RTs pooled by condition hints that although all of the stimuli were discriminable, the natural and high-pass filtered vocalizations from the same individual were perceived as the most similar (longer RTs), and vocalizations from different individuals, one natural and one high-pass filtered, were perceived as the most different (shorter RTs). The only difference in the former condition is the removal of the fundamental from an individual male's bark, whereas the latter condition comprises barks from different individuals and additional high-pass filtering of one of the barks. Thus, the apparent difference in how JFN perceived these conditions is somewhat expected. Laboratory methods similar to those used here can test future hypotheses on vocal signaling in sea lions and investigate the potential impacts of anthropogenic noise on communication.

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Chapter 90
Hearing Sensation Changes When a Warning Predicts a Loud Sound in the False Killer Whale (*Pseudorca crassidens*)

Paul E. Nachtigall and Alexander Y. Supin

Abstract Stranded whales and dolphins have sometimes been associated with loud anthropogenic sounds. Echolocating whales produce very loud sounds themselves and have developed the ability to protect their hearing from their own signals. A false killer whale's hearing sensitivity was measured when a faint warning sound was given just before the presentation of an increase in intensity to 170 dB. If the warning occurred within 1–9 s, as opposed to 20–40 s, the whale showed a 13-dB reduction in hearing sensitivity. Warning sounds before loud pulses may help mitigate the effects of loud anthropogenic sounds on wild animals.

Keywords Learning to change hearing sensation • Anthropogenic sound mitigation • Warning sounds • Avoidance learning • Hearing protection • Loud sound mitigation • Sound avoidance learning

1 Introduction

Loud anthropogenic sounds have been shown to be associated with the stranding of whales and dolphins (Evans and England 2001). Current mitigation procedures to protect whales and dolphins focus on finding and avoiding marine mammals. Given the rapid movement and difficulty of detecting many marine mammals (Madsen et al. 2005), alternative mitigation strategies might be a reasonable augmentation to current efforts. Recent work has demonstrated that a whale was capable of changing

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its hearing sensitivity while it echolocated (Nachtigall and Supin 2008; Supin et al. 2008), perhaps to protect its hearing from its own intense (Møhl et al. 2003) emitted pulses. That result stimulated us to examine whether a whale would similarly protect its hearing when given a warning sound before receiving a loud sound (Nachtigall and Supin 2013).

2 Methods

Hearing sensitivity was measured using auditory evoked potentials (AEPs; Supin et al. 2001). The whale had been trained to station within a hoop while wearing surface electrodes. The subject was a female false killer whale, *Pseudorca crassidens*, estimated to be 35+ year old and trained to accept suction-cup electrodes for brain-potential recording (the active electrode at the vertex and the reference one at the dorsal fin), to swim into a hoop station, and to listen to the test sound stimuli. The sounds were played through a piezoceramic transducer positioned 1 m in front of the hoop station. The test sounds were trains of tone pips, 16 pips/train at a rate of 875/s, each pip containing eight cycles of 20-kHz carrier frequency. These trains were presented at a rate of 20/s during the test period that varied randomly from trial to trial, either from 1 to 9 s (in one series) or from 20 to 140 s (in another series). Levels of the test sounds varied up and down from 80 to 120 dB re 1 μPa in 5-dB steps. In a series of 1- to 9-s-long signals, 1 level was presented during a trial; in a series of 20- to 140-s-long signals, 1–5 levels were presented during a trial. These test sounds evoked rhythmic brain potentials (AEPs) following the rate of the tone pips, i.e., 875/s. The AEPs were picked up through suction-cup electrodes, amplified, analog-to-digital converted, and averaged online within every trial and additionally off-line among the trials. The averaging procedure allowed extraction of AEPs from the background noise and detection of AEPs as low as tens of nanovolts. The extracted rhythmic AEPs were Fourier transformed to obtain their frequency spectra. The spectrum peak magnitude at the stimulation rate (875 Hz) was taken as the response magnitude that was plotted as a function of test-signal level. The level resulting in zero response magnitude was taken as a threshold. The baseline trials contained only these test sounds. After the baseline data were obtained, the conditioning trials were presented. In the conditioning trials, a loud sound immediately followed the test sound. The loud sound was a 20-kHz tone at a level of 170 dB re 1 μPa lasting 5 s. In total, the results are based on 47 baseline trials, 201 conditioning trials of 1- to 9-s-long signals, and 139 conditioning trials of 20- to 140-s-long signals.

3 Results and Discussion

Baseline AEP dependence on test-sound level and an auditory threshold were first established for a 20-kHz tone. Faint test stimuli from 80 to 120 dB re 1 μPa were used within the open Kane'ohe Bay environment. In a second phase, the test sound

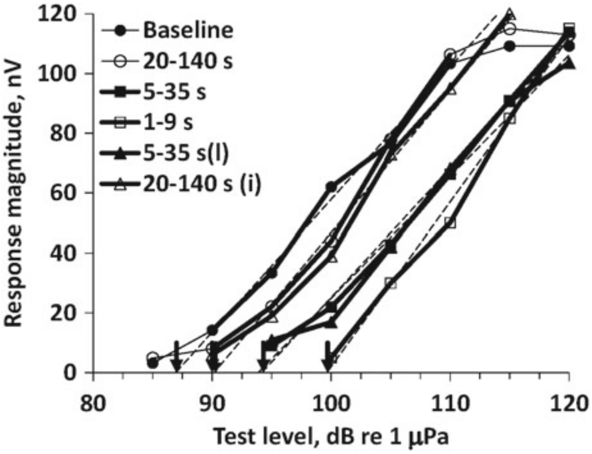

Fig. 90.1 Auditory evoked potential (AEP) root-mean-square magnitude as a function of test sound level. Base, baseline, no loud tone; 1–9 s and 20–140 s, loud tones delayed 1–9 and 20–140 s, respectively. *Arrows mark* baseline threshold (B) and conditioned threshold (C). From Nachtigall and Supin (2013)

was followed by a sudden increase in amplitude up to 170 dB re 1 µPa. Thus the faint test sounds took on the role of a conditioning stimulus signal that warned of the ensuing loud (unconditioned stimulus) sound. After a few trials, the test stimuli revealed a substantial reduction in hearing sensitivity before the loud sound. If the delay between the warning tone onset and loud tone was short (varied randomly from 1 to 9 s), the whale increased its hearing thresholds (reduced sensitivity) by ~13 dB (Fig. 90.1).

Interestingly, when the delay was longer (varied from 20 to 140 s), the shift in sensitivity was negligible. Any unconditioned sensory effect, such as an overall temporary threshold shift, should have been the same irrespective of the relationship between conditioning and loud sounds. Thus the data indicate that (1) the whale learned to change hearing sensitivity when warned that the loud sound was about to arrive and (2) the learning acted only when warnings were immediate. Most often when learning is discussed, operant conditioning with positive reinforcement is considered as the main process operating to change behavior in some manner. The conditioning in this hearing change may not be operating in a traditional operant conditioning paradigm at all but may well be operating in a classical conditioning mode. In classical, or Pavlovian, conditioning, an unconditioned stimulus (UCS) produces an unconditioned response (UCR). In this case, the loud sound (UCS) may have produced an UCR of dampening the hearing sensation levels. The warning sound was likely learned because the conditioned stimulus (CS) preceding the unconditioned stimulus. When the UCS was repeatedly paired with the CS, it subsequently produced the whale's UCR of dampening the hearing sensation. The key learning factor was that the CS came to elicit the same response as the UCS. Alternatively, it might also be thought of in terms of an avoidance conditioning paradigm where the animal learned to avoid the loud sound by dampening the hearing of it. Other animals' motivation for avoiding loud sounds is well established. Rats learn as quickly to avoid loud sound as they do to avoid electric shock (Belluzzi and Grossman 1969).

These sensation level changes nearly equal those of humans plugging their fingers with their ears. This sensitivity change suggests that a neutral signal just before the introduction of loud anthropogenic sounds like sonar or air gun pulses may be a way to condition wild animals to self-mitigate the effects of loud sounds. It is not unreasonable to assume that the wild animals will quickly learn to reduce hearing sensitivity when they hear a warning sound predicting the arrival of a loud sound, reinforced by the avoidance of negative effects of loud sounds. Further work in this area is required to verify whether this procedure of providing a warning sound before an intense anthropogenic sound might be an effective mitigation technique for application to sonar signal design and the presentation of warning signals before air gun array impulses, but these initial results appear promising. This work was based on efforts demonstrating hearing sensation changes during echolocation. The bottlenose dolphin (Li et al. 2012) and the harbor porpoise (Linnenschmidt et al. 2012) have also have been demonstrated to adjust hearing sensation levels during echolocation. Perhaps other echolocating cetaceans will also demonstrate the possibility of self-mitigation of the effects of loud impulsive sound by learning to change hearing sensation levels when warned, but this assumption requires empirical demonstration.

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Chapter 91
Does Masking Matter? Shipping Noise and Fish Vocalizations

Sarah T.V. Neenan, Rayner Piper, Paul R. White, Paul Kemp, Timothy G. Leighton, and Peter J. Shaw

Abstract Shipping creates large near-field background noises at levels similar to or higher than fish vocalizations and in the same critical bandwidths. This noise has the potential to "mask" biologically important signals and prevent fish from hearing them; any interference with the detection and recognition of sounds may impact fish survival. The Lombard effect, whereby vocalizations are altered to reduce or exclude masking effects, is an adaptation that has been observed in mammals and birds. Research is needed to establish whether the Lombard effect occurs in fish to gain a better understanding of the implications of noise pollution on fish populations.

Keywords Lombard effect • Anthropogenic • Vessel • Communication

1 Trends in Vessel Noise

The most widespread source of marine anthropogenic underwater noise pollution is from vessels (Firestone and Jarvis 2007; Jensen et al. 2009). Higher levels of marine traffic have led to low-frequency background noise in the ocean increasing 32-fold since the 1950s (Malakoff 2010). Several factors have contributed to this increase. For example, the worldwide commercial fleet, consisting of tankers, dry bulk vessels, container ships, and other large ocean-going vessels, has grown from ~30,000 vessels (~85,000,000 gross tons) in 1950 to 89,899 vessels (~605,000,000 gross tons) in 2003 (Ross 1993; Southall 2005). Worldwide, noncommercial vessels,

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including recreational craft and private boats, have also increased (although actual numbers cannot be stated because no official log exists). Additionally, port turnaround times are shorter, resulting in ships spending more days per year at sea and vessels have greater average speeds, propulsion power, and propeller tip speeds (Ross 1976, 1993; Southall 2005; McDonald et al. 2006). Ross (1976, 1982, 1993) presented data that indicated that sound levels had increased by 15 dB between 1950 and 1975 as a direct result of shipping activities. These trends are certain to continue, posing unique challenges for aquatic animals (Firestone and Jarvis 2007).

2 Masking

The turbid conditions present in much of the underwater environment, e.g., in coastal areas, means that many species rely on sound rather than vision to decipher information about their surroundings. Many fish species use ambient biotic and abiotic sounds emanating from objects to interpret changes in their acoustic environment, creating an "acoustic view" (Bregman 1990). Sound is an ideal means of communication in the aquatic environment because it can be propagated rapidly over great distances (five times faster than in air, 1,560 ms^{-1} at 25 °C) and is not attenuated as quickly as other signals such as light or chemicals (Hawkins and Myrberg 1983; Amoser and Ladich 2003; Andersson 2011). Fish use hearing to perceive and navigate their environment, so the ability to create an auditory scene and correctly interpret the acoustic information gleaned is crucial for survival (Myrberg 2001). Sound can inform an individual as to the whereabouts of food, competitors, predators, and potential mates through the perception of intended and/or unintended acoustic signals in the environment (Myrberg 1978).

When considering noise pollution, "noise" is taken to mean any sound that has the potential to negatively impact marine life (van der Graaf et al. 2012). Noise may be generated for an explicit purpose, such as locating submerged objects or fish shoals or measuring environmental features, or it may be an unwelcome by-product of industrial activities, such as the construction of infrastructure or the movement of vessels. Anthropogenic noise can potentially affect any animal that comes into contact with it and is capable of hearing it (Slabbekoorn et al. 2010). Noise is especially deleterious to fish because it often has frequencies within their hearing thresholds (Scholik and Yan 2002). Both physiological and behavioral changes have been observed in fish as a result of anthropogenic noise sources (Popper et al. 2003). Masking (when the detection of one sound is impaired by the presence of another) has been proven to occur in terrestrial animals (e.g., Fletcher 1940), and it is possible that it is occurring in fish. Shipping creates large near-field background noise at levels similar to those of fish vocalizations and in the same critical bandwidths so noise pollution could directly affect the survival of fish populations by decreasing their ability to hear and respond to biologically important signals.

Over 800 fish species from more than 109 families are known to vocalize, with many more suspected of doing so (Slabbekoorn et al. 2010). Fish, including some key UK commercial species such as cod and haddock, vocalize for a variety of reasons:

- to attract mates (e.g., damselfish, Parmentier et al. 2006; blennies, De Jong et al. 2007; croakers, Connaughton et al. 2002; drums, Locascio et al. 2012);
- to establish territory (e.g., toadfish, McKibben and Bass 1998; minnows, Nicoletto and Linscomb 2007);
- while foraging (e.g., gurnards, Amorim et al. 2004; seahorse, Anderson 2009);
- while competing for food (e.g., cichlids, Lamml and Kramer 2008; piranhas, Kastenhuber and Neuhauss 2011);
- as a fright response (e.g., croakers, Connaughton et al. 2002); or
- to aggregate for spawning and synchronize the release of gametes (e.g., catfish, Papes and Ladich 2011).

Masking from anthropogenic sources can interfere with these vocalizations or reduce the distance at which these biologically important vocalizations can be detected by the fish. This is due to the introduced noise raising the ambient level and decreasing the signal-to-noise ratio, which reduces the signal detection distance and thus causes the detection of a signal to become more difficult (Andersson 2011). This masking effect could make it difficult for the fish to locate and communicate with conspecifics (other members of the same species) and prevent the biologically important sounds associated with successful reproduction from being heard. *Gobius cruentatus* (red-mouthed goby), *Sciaena umbra* (brown meagre), and *Chromis chromis* (Mediterranean damselfish) all significantly increased their detection threshold levels to hear conspecific sounds when exposed to 132-dB cabin-cruiser noise reproduced in the laboratory (Codarin et al. 2009). It has also been shown that wind, temperature gradients, substrate, and foliage can all restrict or enhance the distance over which signals can be used for communication in terrestrial environments (Mann and Lobel 1997). Therefore, anthropogenic sounds may work synergistically with the underwater environment to increase the adverse effects of masking.

Wollerman and Wiley (2002) suggested that noisy conditions can interfere with mate selection. Mating calls masked by unnatural noise means that only the loudest individual or an individual displaying a certain pitch will be heard and, therefore, mate successfully. This could ultimately lead to a decrease in the genetic diversity of the population. When heterospecific vocalizations are masked, foraging is energetically more costly because prey are harder to locate and predation risks are higher as warning sounds from approaching predators are missed. Moreover, nonvocal species may use the vocalizations of other species as an aid to navigation; sharks monitor the sounds of struggling fish to locate and capture them as prey (e.g., Myrberg et al. 1976). Any excess noise in the environment can, therefore, decrease the shark's chances of successful foraging.

The larval stage is a crucial time for development and survival in the life cycle of many marine animals (Ohs et al. 2009). Larvae are much more susceptible to predation because their ability to swim is limited. Noise pollution from anthropogenic sources can interfere with larval settlement and recruitment processes because some larvae use the ambient ocean noise to orientate and locate desirable habitats (different habitats have distinct acoustic signatures [Montgomery et al. 2006; Radford et al. 2010]). Larvae unable to locate a suitable site in which to settle will die from lack of food or predation; this will impact on the species' population if it should happen to multiple individuals in the same year or spawning cycle. Reef-associated larvae are especially at risk because vessel noise is commonplace around reefs and can impede the detection and selection of the appropriate settlement habitats of many species (Holles et al. 2013).

Furthermore, masking can cause problems for parents tending their young. The adults need to hear the begging calls of progeny or cues will be missed and the offspring's survival may be compromised (Kilner and Hinde 2008). Territoriality can also be affected by masking because many fish, such as the *Abudefduf saxatilis* (sergeant fish), are known to mark and defend their territory using sound (Maruska et al. 2007). The red-mouthed goby was observed to reduce territoriality in the presence of boat noise, and the resultant increased aggressive contests had a subsequent detrimental effect on reproduction (Sebastianutto et al. 2011). In response to anthropogenic noise, some marine mammals have simply stopped vocalizing altogether (Weilgart 2007). The lack of signals between conspecifics means that behavior necessary for a population's survival may not naturally occur.

3 The Lombard Effect

Throughout the paleontological record, there are examples of species having evolved to overcome the perturbations they faced. However, the rapid rate at which noise is increasing in the ocean may not allow such mechanisms to evolve as quickly as is necessary. Currently, over 77 fish species for which audiograms exist are known to have hearing thresholds within the same frequency range as the noise produced by vessels. The exact frequency spectrum of the noise is altered depending on the type of vessel. Individuals may compensate for the increase in vessel noise by changing the amplitude (Scheifele et al. 2005; Holt et al. 2009), duration (Foote et al. 2004), repetition rate, and/or frequency of the sounds they produce. This effect, which has the potential to overcome the effects of masking, is known as the Lombard effect, the automatic and involuntary change in the intensity of vocalizations in the presence of background noise needed to maintain a constant signal-to-noise ratio (Coffey 2012). To date, the Lombard effect has not been greatly studied in fish, but other animals have shown that this effect can help overcome problems caused by masking (Table 91.1).

Research is needed to determine whether the Lombard effect occurs in fish. If this phenomenon does occur, then serious concerns regarding the effects of vessel noise on vocalizing fish populations may be unfounded. However, altering vocalizations may be metabolically expensive and necessitates that a fish's communication range is not already maximized (Jensen et al. 2009). Furthermore, it has been hypothesized that fish vocalizations are dependent on the size of the fish and individuals may not physically possess the ability to alter their vocalizations.

Table 91.1 Studies that show evidence of the Lombard effect being used to overcome masking

Class	Taxa	Observed effects	Reference
Birds	*Luscinia megarhynchos* (free-ranging nightingale)	Males were recorded singing at higher sound levels when in noisier locations	Brumm (2004)
Arthropods	*Schizocosa ocreata* (ground-dwelling wolf spider)	Females, who communicate via vibrations, showed changes in courtship behavior, receptivity, and mating success when exposed to white noise	Gordon and Uetz (2012)
Mammals	*Delphinapterus leucas* (St. Lawrence River beluga)	Increased the intensity of vocalizations in the presence of boat noise	Scheifele et al. (2005)
	Orcinus orca (killer whales)	Respond to vessel noise by increasing their vocalizations by 1 dB for every 1-dB increase in background noise	Holt et al. (2009)
Amphibians	*Litoria ewingii* (brown tree frogs)	Altered the pitch of their advertisement calls in the presence of traffic noise	Parris et al. (2009)
	Crinia signifera (common eastern froglets)	Altered the pitch of their advertisement calls in the presence of traffic noise	Parris et al. (2009)

The occurrence of the Lombard effect may differ according to species and/or individual differences, the type of sound source, its frequency and intensity, or other factors such as season and topography. Studies to determine whether the Lombard effect occurs in fish should seek to assess a range of environmental conditions under which the effect may occur and relate these to fish life-cycle stages. Primarily, any masking problems encountered during reproductive phases need to be addressed to ascertain whether or not there could be implications for population survival.

If it can be proven that fish species do alter the pitch, intensity, or duration of their vocalizations to remain audible to conspecifics, then behaviors such as aggregated migration, courtship, and spawning can occur unhindered in the presence of underwater noise pollution. However, if the Lombard effect is not observed in fish, then the masking of vocalizations by anthropogenic noise should be regarded as a serious threat to vocalizing fish species.

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Chapter 92
Noise Mitigation During Pile Driving Efficiently Reduces Disturbance of Marine Mammals

Georg Nehls, Armin Rose, Ansgar Diederichs, Michael Bellmann, and Hendrik Pehlke

Abstract Acoustic monitoring of harbor porpoises (*Phocoena phocoena* L., 1758) indicated a strongly reduced disturbance by noise emitted by pile driving for offshore wind turbine foundations insulated by a big bubble curtain (BBC). This newly developed noise mitigation system was tested during construction of the offshore wind farm Borkum West II (North Sea). Because porpoise activity strongly corresponded to the sound level, operation of the new system under its most suitable configuration reduced the porpoise disturbance area by ~90%. Hence, for the first time, a positive effect of a noise mitigation system during offshore pile driving on an affected marine mammal species could be demonstrated.

Keywords Big bubble curtain • Sound exposure level • Noise pollution • Offshore wind farm • Harbor porpoise *Phocoena phocoena*

1 Introduction

Against the backdrop of an increasing utilization of offshore wind energy (Mann and Teilmann 2013), noise protection is an important issue because underwater pile driving during the founding of offshore wind turbines (wind energy areas [WEAs]) comes along with strong noise emissions causing disturbance and potential injury to marine mammals. To deal with this situation until now, different kinds of noise mitigation systems were developed and evaluated according to their noise mitigation

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potential (e.g., Würsig et al. 2000; Illingworth and Rodkin 2007; Nehls et al. 2007; Griessmann et al. 2010; Stokes et al. 2010; Koschinski and Lüdemann 2011; Wilke et al. 2012; Rustemeier et al. 2012a, b; Spence and Dreyer 2012; Bureau of Ocean Energy Management 2013).

Within the framework of the project HYDROSCHALL-OFF BW II (Pehlke et al. 2013), a new noise mitigation system, a prelaid big bubble curtain (BBC), was developed and its consequences for the presence of the harbor porpoise (*Phocoena phocoena* L., 1758) was tested during pile-driving activity for the offshore wind farm Borkum West II (TRIANEL WINDKRAFTWERK BORKUM GmbH & Co.KG) in the German Bight (North Sea).

In the southern North Sea, harbor porpoises are the most common marine cetaceans (Gilles et al. 2009) potentially prone to noise pollution by pile driving (e.g., Brandt et al. 2011; Dähne et al. 2013). These animals orient themselves acoustically by emitting high-frequency click sounds. For the protection of this and other species listed in the EC Habitats Directive (European Commission 1992), the German Federal Maritime and Hydrographic Agency (2010) and the German Federal Environment Agency (2011) imposed restrictions according to noise protection norms (160 dB_{SEL} [sound exposure level] and 190 dB_{Lpeak} [peak level] at 750 m distance from the sound source), supporting the further development of effective noise mitigation systems in German waters.

Positive effects of noise mitigation systems on marine mammals were not yet demonstrated under real offshore conditions, a situation that was changed by this study.

2 Materials and Methods

The wind farm Borkum West II, positioned 45 km north of Borkum Island (North Sea), consists of 40 wind turbines (40 more WEAs are planned for the future) and a transformer station. During foundation work for the WEA tripod constructions, 120 piles were driven into the sediment by a hydraulic hammer. The tested noise mitigation system, a BBC developed by HYDROTECHNIK Lübeck GmbH, consisted of jet nozzle hoses into which compressed air was pumped. The prelaying principle of the BBC, i.e., circular deployment of the nozzle hose(s) around the planned position of a turbine foundation before arrival of the jack-up vessel and then connecting and operating the hose after the jack-up vessel was positioned, was successful in causing no delays for the process of wind farm construction. The special configuration BBC 2, which was used here for certain analyses, consisted of a circular single hose of 560 m length, with small nozzles (1.5 mm) at a short distance from each other (30 cm).

Within the project, extensive data from 26 C-POD positions covering different distances between 0.4 and 36 km from the piling location and up to four hydroacoustic points of measurement were available (Pehlke et al. 2013), adding up to a worldwide exceptional data pool for investigating the response of harbor porpoises to underwater sound originating from noise-mitigated and uninsulated pile driving. Noise levels during ramming activity were standardized to a distance of 750 m from the sound source.

Detection rates of harbor porpoises according to pile-driving activity were assessed on a temporal scale of hours (PPM/h). Original PPM/h values were converted into modeled values (linear mixed-effects [LME] model) to account for random effects of different WEA and C-POD stations as well as for C-POD sensitivity differences. Due to a left-skewed distribution of converted PPM/h values and the presence of zero inflation (48% zero values in the dataset), the new parameter δPPM/h was derived from PPM/h by the following standardization procedure. Average detection rates from a period of 9 h before ramming (full hours $T_{-10\,\mathrm{h}}$ to $T_{-2\,\mathrm{h}}$), under the condition that no ramming took place in the preceding 24 h (until $T_{-34\,\mathrm{h}}$), were assumed to be uninfluenced by pile-driving activity and are defined as the reference parameter PPM·s. The standardized parameter δPPM/h was defined as the difference between PPM/h values obtained during pile-driving activity and the reference parameter: δPPM/h = PPM/h − PPM·s. If δPPM/h < 0, then the detection rates during ramming activities were lower than the reference value before pile driving.

3 Results

The BBC configuration BBC 2 (circular single hose with small nozzles at a short distance to each other) under a full air supply of 0.32 m^3 air/(min · m hose) turned out to be the best compromise of efficiency and practicability under offshore pile-driving conditions. Its noise mitigation effect ranged between 9 and 13 dB (mean 11 dB) for the 50th percentile of the SEL (SEL50) and between 10 and 17 dB (mean 14 dB) for the peak level, which was rated to be efficient. Noise mitigation of a BBC 2 worked best at higher frequencies (Fig. 92.1).

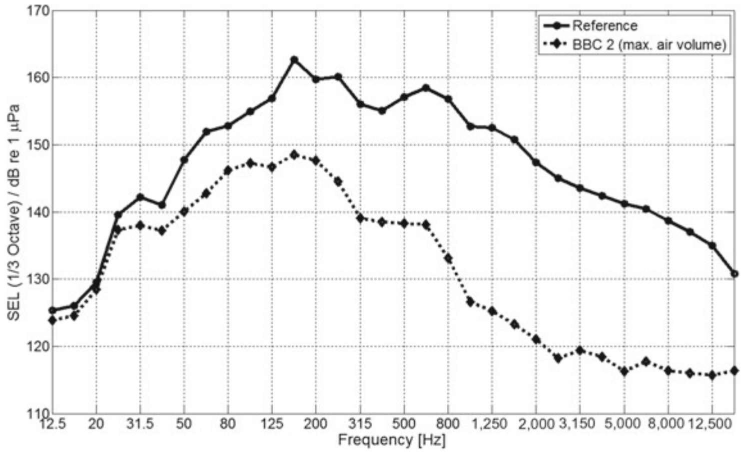

Fig. 92.1 Third-octave spectra of the standardized (750 m distance) single-event level during reference rammings (without noise mitigation system) compared with rammings insulated by a big bubble curtain (BBC) 2 configuration (circular single hose with small nozzles at a short distance to each other under maximum air supply), demonstrating the good noise mitigation of a BBC 2, particularly at higher frequencies. *SEL* sound exposure level. Values are means

Table 92.1 Dataset available for the analyses of the effect of different pile-driving sound levels on harbor porpoise activity

Sound level, dB_{SEL50}	No mitigation	BBC 2	BBC 1	Other
<135	60	266	120	83
135–140	57	206	118	130
140–145	195	135	84	57
145–150	237	33	58	76
150–155	147	31	12	26
155–160	92	6	14	28
>160	57	0	0	5

dB_{SEL50}, Sound level at 50th percentile of sound exposure level; BBC 2, big bubble curtain configuration with a circular single hose with small nozzles at a short distance to each other under maximum air supply; BBC 1, BBC configuration with hose with bigger nozzles at larger distance to each other compared with BBC 2; other, other BBC configurations. Available data had to include acoustic data and corresponding detection rates. Note the good noise mitigation of the BBC 2. See also Fig. 92.2 and Table 92.2

A possible effect of ramming noise pollution at different sound levels (5 dB_{SEL50} classes) on harbor porpoise detection rates was investigated over a dataset that had to include acoustic data and PPM/h rates of pile-driving activities insulated by different BBC configurations as well as without noise mitigation (Table 92.1).

Detection rates (PPM/h) during pile-driving activity were compared with those in a reference period before rammings. The standardized parameter δPPM/h described the amount of the effect (see Section 2). A strong correlation of increasing disturbance of harbor porpoises with increasing sound levels of pile driving (the latter corresponding to shorter distances from the sound source under similar noise-mitigating conditions) was uncovered (Fig. 92.2). The limit of a disturbance effect on harbor porpoises ranged between 140 and 145 dB_{SEL50}. From 145 dB_{SEL50} upward, a significant disturbance effect occurred (Table 92.2). The lowest porpoise detection rates were found for sound levels >160 dB_{SEL50}, tantamount to an almost total expulsion of animals. However, with the dataset available for the analysis of the sound level dependence of detection rates, those sound levels were not reached under the operation of a BBC 2 (Table 92.1), underlining the substantial noise-mitigating effect of this BBC configuration. Pointing in the same direction, at other sound levels causing a significant disturbance effect on harbor porpoises (down to 145 dB_{SEL50}), only few data were available when a BBC 2 was active (Table 92.1).

Combining both results, the considerable noise mitigation by a BBC 2 (Fig. 92.1), and the sound level-dependent disturbance effect on harbor porpoises (Fig. 92.2), logically induces a reduced disturbance of harbor porpoises during pile driving under noise mitigation by BBC 2, which could be further specified. Based on a sound propagation function established during the project (Pehlke et al. 2013), a theoretical distance to a sound source of known intensity was computable. For harbor porpoises, a radius of disturbance of ~15 km was obtained for uninsulated pile-driving activities.

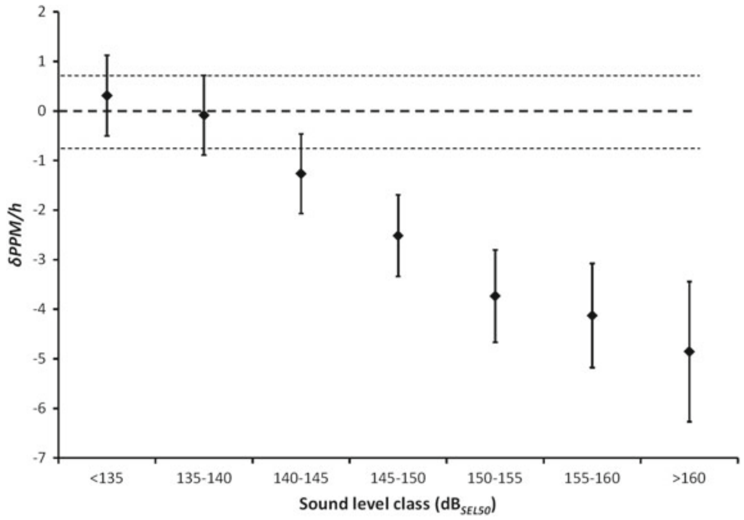

Fig. 92.2 Effect of sound level at 50th percentile of the SEL (5 dB$_{SEL50}$ classes) at rammings on standardized harbor porpoise detection rates (δPPM/h; difference between the temporal scale of hours [PPM/h] and reference parameter of detection rates uninfluenced by pile-driving activity [PPM·s]). Values are means ± SE against average detection rates during a reference period. *Dotted horizontal lines*, mean ± SE of reference parameter

Table 92.2 Values during pile-driving activity at different sound levels (5 dB$_{SEL50}$ classes)

Sound level, dB$_{SEL50}$	*N*	δPPM/h ± SE	df	*t* value	*P* value	Significance
<135	529	0.30839 ± 0.81168	381	0.37994	0.7042	NS
135–140	511	−0.08752 ± 0.80327	381	−0.10895	0.9133	NS
140–145	471	−1.26633 ± 0.80348	381	−1.57606	0.1158	NS
145–150	404	−2.51656 ± 0.82147	381	−3.06350	0.0023	**
150–155	216	−3.73560 ± 0.93069	381	−4.01381	0.0001	***
155–160	140	−4.12671 ± 1.05013	381	−3.92970	0.0001	***
>160	62	−4.85539 ± 1.41231	381	−3.43790	0.0007	***

δPPM/h standardized harbor porpoise detection rate (difference between the temporal scale of hours [PPM\h] and reference parameter of detection rates uninfluenced by pile-driving activity [PPM·s]), *N* number of data. Significance levels for *P* values: *NS* not significant ($P > 0.05$); **, highly significant ($P \leq 0.01$); ***, most significant ($P \leq 0.001$)

During the operation of BBC 2 under a full air supply, the radius of disturbance was reduced to ~5 km under a given average noise mitigation of 11 dB$_{SEL50}$. Hence, the application of a BBC 2 reduced the area of equal sound levels by ~90% compared with uninsulated pile-driving activities that, in turn, reduced the area of potential disturbance by pile-driving activities for harbor porpoises by the same proportion.

4 Discussion

During construction of the offshore wind farm Borkum West II, a new noise mitigation system, the BBC, was, for the first time, integrated into the usual construction process of an offshore wind farm without causing any delays. Noise mitigation of the new system resulted in a strong reduction of the spatial and temporal disturbance effects on harbor porpoises. This demonstrated that a positive effect for a species of public interest was achievable by insulation of noise emissions resulting from offshore pile driving.

Operation of the BBC 2 reduced the potential area of disturbance by pile driving for harbor porpoises by 90%. Accordingly, under the assumption of a relatively homogeneous distribution of harbor porpoises on a short-term temporal scale (during operation of a BBC 2) within the restricted spatial range of the study area (tens of kilometers), the average number of disturbed animals would be reduced by 90% as well compared with pile driving without noise mitigation.

Experiences from project HYDROSCHALL-OFF BW II form a substantial base regarding future application of noise mitigation systems as part of offshore wind farm development in Germany. However, findings of other projects indicate that the results of this project may be only partly applicable to other locations; under different conditions, it was not always possible to achieve the noise mitigation rates obtained during this project (e.g., Würsig et al. 2000; Illingworth and Rodkin 2007; Nehls et al. 2007).

Ongoing discussions regarding the assessment of pile-driving noise clearly show that there is great public interest in a description and evaluation of harbor porpoise response to noise pollution (e.g., Brandt et al. 2011; Dähne et al. 2013). The project provided new insights in this respect. However, some questions remained open that should be addressed in future projects. Besides further technical development of bubble curtains, it will be important to investigate their mode of action under different conditions as well as to describe influencing parameters on the sound mitigation of a BBC (Pehlke et al. 2013). As for the harbor porpoise response, it would be desirable to further evaluate the effects of frequency-dependent noise mitigation of a BBC as well as of different durations of ramming periods on the spatiotemporal activity patterns of these animals in future.

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Chapter 93
Noise Impact on European Sea Bass Behavior: Temporal Structure Matters

Yik Yaw Neo, Johanna Seitz, Ronald A. Kastelein, Hendrik V. Winter, Carel ten Cate, and Hans Slabbekoorn

Abstract Anthropogenic sounds come in different forms, varying not only in amplitude and frequency spectrum but also in temporal structure. Although fish are sensitive to the temporal characteristics of sound, little is known about how their behavior is affected by anthropogenic sounds of different temporal patterns. We investigated this question using groups of *Dicentrarchus labrax* (European sea bass) in an outdoor basin. Our data revealed that the temporal pattern of sound exposure is important in noise impact assessments.

Keywords *Dicentrarchus labrax* • Anthropogenic sounds • Intermittency • Amplitude fluctuation • Stress response

1 Temporal Variation of Anthropogenic Sounds

Fish are known to use sounds for soundscape orientation (Simpson et al. 2004, 2005; Slabbekoorn and Bouton 2008), conspecific communication (Ladich 1997; Verzijden et al. 2010), and predator–prey interactions (Holt and Johnston 2011; Ward et al. 2011). However, their extensive use of sound may be hindered by the underwater anthropogenic noise produced by human activity in and around the

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water (Slabbekoorn et al. 2010; Popper and Hawkins 2011). Anthropogenic sounds originate from various sources, including underwater explosions, seismic surveys, sonar exploration, offshore construction, commercial shipping, and recreational boating. These sounds differ from each other in terms of their frequency range, amplitude fluctuation, and temporal structure. Nevertheless, many of these sound features have rarely been examined in noise impact assessments.

Although fish are known to be sensitive to the temporal characteristics of sounds, which may carry important information (Nelson and Johnson 1972; Marvit and Crawford 2000; Wysocki and Ladich 2002), very little is known about how their behavior may be affected by the temporal characteristics of anthropogenic noise. The temporal parameters of interest include sound intermittency, repetition rate, pulse duration, and pulse regularity. For example, anthropogenic sounds can be continuous (e.g., wind turbines and vessel noise) or intermittent (e.g., seismic air guns and pile-driving noise). Moreover, the sound amplitude may be consistent or fluctuate over time depending on the characteristics or movements of the sound sources. Therefore, to assess the impact of anthropogenic noise, we need a better understanding about the extent to which different sound features contribute to the impact.

2 Behavioral Assessment of Noise Impact on Fish

To assess the contribution of temporal parameters to noise impact on fish behavior, we exposed groups of four European sea bass in an outdoor basin (7×4×2 m) to artificial sounds with different temporal structures. The behavior of the fish was video recorded and analyzed with computer software (Logger Pro 3.8.5.1, Vernier Software and Technology). We were able to visualize the swimming patterns of the fish throughout the entire trial duration before, during, and after sound exposure (Fig. 93.1). We

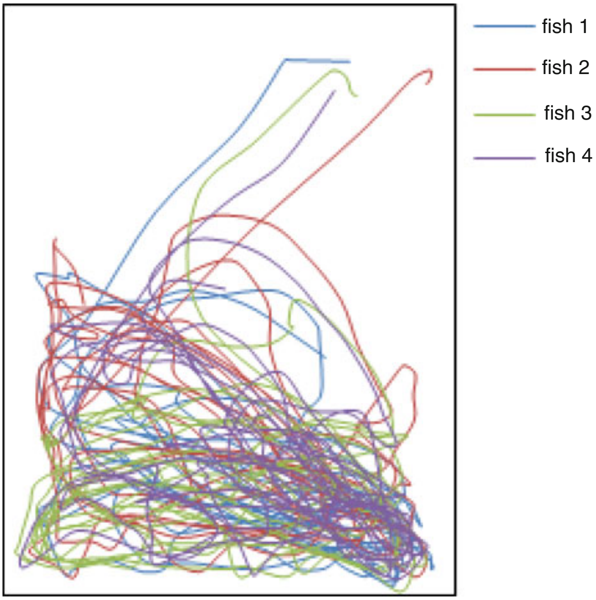

Fig. 93.1 Typical swimming tracks of 4 fish for 5 min at the onset of sound exposure

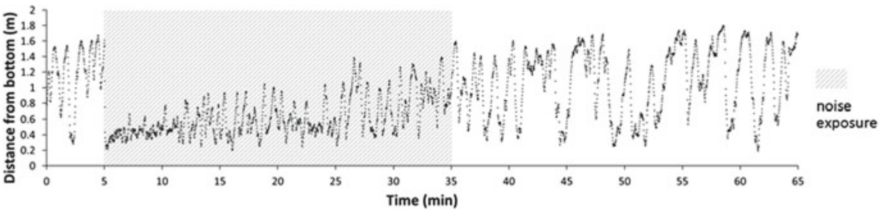

Fig. 93.2 Time series plot showing the swimming depth change at the onset of sound exposure and its recovery

calculated several behavioral parameters, such as swimming speed, swimming depth, and group cohesion, and examined how these parameters changed over time (Fig. 93.2).

3 Consequences for Current Practices

We found evidence that sound exposure triggered anxiety-related behaviors in our test fish by changing their swimming patterns and spatial distribution. Moreover, sounds with different temporal structures differed in their effect strength. This calls for a reconsideration of current practices in noise impact assessments, which usually take only exposure levels and duration into account but not the temporal patterns of sound exposure. Most noise impact assessments typically evaluate the severity of sound impact on aquatic organisms based on several standardized metrics, such as root-mean-square (rms) sound pressure level (SPL_{rms}), zero-to-peak sound pressure level ($SPL_{z\text{-}p}$), sound exposure level (SEL), or cumulative SEL (SEL_{cum}), assuming that higher values denote more severe impact. However, our findings suggest that depending on the temporal structure, a sound exposure at a lower SPL or SEL may actually have a stronger impact on fish swimming behavior. Therefore, a better characterization and description of temporal variation in sound exposure is needed for future noise impact assessments.

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Chapter 94
Does Noise From Shipping and Boat Traffic Affect Predator Vigilance in the European Common Hermit Crab?

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Abstract The effect of noise on predator vigilance in *Pagurus bernhardus* was explored in this study. Latency of the first response, emergence time, and response type were measured from hermit crabs during continuous and variable vessel noise and two controls. The mean (±SE) response latency was longer for the noise treatments (continuous, 18.19 ± 2.78 s; variable, 11.39 ± 1.48 s) than for the controls (ambient, 7.21 ± 0.82 s; silent, 6.66 ± 0.95 s). Response type and emergence time were not significantly affected but were more variable during the noise treatments than during the controls. Noisy conditions may increase predation risk, suggesting potential fitness consequences for invertebrates.

Keywords Invertebrates • Escape response • Predation • Survival • Distraction

1 Introduction

Anthropogenic noise in the world's oceans has been increasing over the last few decades (Andrew et al. 2002), and even though the oceans contain many natural noises, the ability of marine life to cope with the introduction of human-generated noise is uncertain in many cases. Much of the immediate concern has been on the effects of high-intensity impulsive noise on animals with sophisticated sound production and reception abilities (Southall et al. 2007), but more recent work has emphasized the need to explore the effects of moderate-intensity continuous noise on a wider array of marine animals (Popper and Hastings 2009; Slabbekoorn et al. 2010). Vessel noise belongs to this category and is a ubiquitous presence in nearly all marine habitats. Because of the type of noise, vessel noise is unlikely to have direct

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lethal or sublethal effects, such as direct mortality or physical damage, but because both commercial shipping and recreational boating activities have been increasing (Jasny 2005), understanding the potential for these types of anthropogenic noise to have biologically significant impacts on all marine animals is important.

Marine invertebrates make up a large portion of the ocean's biomass and biodiversity and play important ecological roles as both primary consumers and scavengers in many food webs. However, the effects of anthropogenic noise on this abundant group have not been investigated much until recently. Sound is used by invertebrates to forage, defend territories, deter predators, and settle during development (Tóth and Duffy 2005; Montgomery et al. 2006; Patek et al. 2009), all key biological functions that could have fitness implications if disrupted. Preliminary studies with squid (Fewtrell and McCauley 2012) and crustaceans (Regnault and Lagardere 1983; Payne et al. 2007) have indicated that noise can reduce foraging performance, affect serum biochemistry, and decrease growth and reproduction in some invertebrate species, suggesting the potential for population-level effects.

Being able to detect the presence of a predator in enough time to take appropriate evasive action is of vital importance to the survival of individuals (Ryan et al. 2012), particularly for primary consumers that have many predators. Delayed or suboptimal predator vigilance and response has direct fitness consequences in nature. Boat noise has been shown to distract *Coenobita clypeatus* (Caribbean hermit crab) from responding to predators, with the duration of the noise exposure found to affect how long a response was delayed (Chan et al. 2010a, b). If these effects happen in air, the potential exists for them in the marine environment as well, with potentially greater zones of influence related to the better transmission of sound in water. The goal of this work was to investigate whether two types of anthropogenic noise affected the latency of antipredator response in *Pagurus bernhardus* (common European hermit crab), an abundant marine invertebrate found in many shallow European habitats.

2 Materials and Methods

Fifteen common European hermit crabs, with shell lengths ranging from 7.5 to 11 cm, were collected from Loch Fyne, UK, on 10 December 2012 and transported to the laboratory aquariums at the University of Glasgow, where they were housed in appropriate holding tanks. Experimental treatments were applied in a separate test aquarium that was located in a second quieter laboratory to avoid the addition of noise from the building's seawater filtration system or the exposure of other test specimens while in their holding tanks. The test pool, measuring 80 cm diameter by 20 cm depth, was opaque and made of durable, rubberized plastic with flexible padded panels. It was placed on a thick polystyrene board on a metal storage shelf to minimize transmission of any external vibrations through the floor. A mesh barrier of ~15 cm in diameter was inserted along its perimeter to prevent subjects from wandering into the corners while also allowing them free movement within the central portion of the test pool. At one end of the test pool, two LTC audio SWR-5004 waterproof stereo speakers were hung on clamp stands, angled downward, and arranged opposing each other as close to the water surface as possible, while at the other end of the pool, a predator hide occupying ~1/3 of the pool was constructed by placing two styrofoam boards above the pool, to which black polythene sheeting was attached and hung into the water column, following Scarratt and Godin (1992). A grabbing tool was used to maneuver the dummy predator out from behind the sheeting during each trial. This predator was constructed from a cleaned *Carcinus maenus* crab carapace and plastron that was mounted on a small piece of flat styrofoam board. A second black polythene curtain with a small rectangular viewing window cut out from it was positioned beside the test pool to conceal the researcher throughout the study.

Ambient underwater sound profiles of the holding tanks and the test pool during playback of each treatment were measured before each trial for a period of ~120 s at a sampling rate of 16 kHz with a Wildlife Acoustics SM2+ recorder and HTI-96-MIN hydrophone. Raven Pro 1.4 software (Cornell Lab of Ornithology) was used to measure sound pressure levels (SPLs) from each of these recordings, which were compared before treatment to ensure that noise levels in the test pool were altered appropriately.

The experiment involved four noise treatments obtained from online sound archives, which consisted of two noise treatments (shipping noise and boat noise) and two control treatments (ambient ocean and silence). The shipping noise was recorded in 2012 from a large merchant vessel in St. Lawrence, Canada (Discovery of Sound in the Sea [DOSITS], www.dosits.org; sound courtesy of P. M. Scheifele) and the boat noise was recorded from a small outboard craft with a 150-hp engine approaching at medium speed, which produced a variable level of noise (Sounddogs.com, Inc.). A recording of ambient ocean noise from a novel habitat, Glacier Bay National Park (National Park Service 2012), was used as a positive control. A silent track was created using GarageBand software (Apple, Inc.), which was also used to standardize files to 4 min in duration.

Noise treatments were numbered 1–4 by a volunteer not otherwise involved in the study, and the order in which each hermit crab received each treatment was randomly assigned at the beginning of the study. Hermit crabs received 1 treatment/day over a period of 4 days to minimize habituation to the treatment process. Each treatment was played from an iPad connected to a Pyle PCAU44 stereo amplifier with an MP3 input. Throughout all experimentation periods, the researcher listened to separate music through headphones to avoid hearing which noise treatment an individual crab was experiencing.

After the treatment was started, a hermit crab was transferred from its holding tank to the test laboratory and placed in the middle of the test pool with its shell aperture facing the predator hide so that the hermit crab would have a direct view of the predator when it emerged. The time from when it was placed in the pool until it emerged from its shell was recorded. At least 30 s were then allowed to elapse before predator presentation commenced so that each crab was able to acclimate to the test pool. Crabs were typically observed to resume regular behavior during this interval, defined as that seen when in holding tanks, e.g., filter feeding, “scooping” through gravel, or moving. Predator presentation consisted of gradually advancing the dummy *Carcinus maenas* from its hide toward the test subject. The time at which the crab was seen to first respond to the predator was recorded, defined as the latency of first antipredator response, along with the type of response made by the crab. Once a response was recorded from a particular hermit crab, the dummy predator was retracted back into the hide, the playback was stopped, and the hermit crab was returned to its holding tank. This procedure was then repeated for the next hermit crab. At the end of the experiment, each hermit crab's shell height and aperture diameter were measured and used to calculate shell volume.

A repeated-measures one-way analysis of variance (ANOVA) assuming sphericity and including individual as a random effect was used to compare the effect of noise treatment on predator response latency. A post hoc Tukey's honestly significant difference (HSD) test was then used to determine the significance of individual treatment comparisons. A second repeated-measures ANOVA was used to compare the effects of noise treatment on time to emergence. The effect of treatment on response type was tested with a Fisher's exact test. Finally, Pearson's product-moment correlation tests were performed to determine whether shell volume, day of trial, or noise treatment exposure duration influenced the latency of first response, and any significant correlations were tested with an analysis of covariance (ANCOVA). All tests were carried out using R software (version 2.15.2) at a significance level of $P \leq 0.05$.

3 Results

Preexperiment ambient noise in the holding tanks was similar to that used for the ambient ocean noise treatments (mean SPL of 38 dB re 1 μPa between 1 and 3 kHz), whereas pretreatment ambient noise in the test tank was lower (22 dB re 1 μPa). The ship noise playback resulted in the highest average SPL (58 dB re 1 μPa), but the boat noise playback was also higher than the ambient tank or ambient ocean levels (50 dB re 1 μPa).

Mean (±SE) latency of first antipredator response was higher for the two noise treatments than for the two quiet treatments, with a latency of 18.19 ± 2.78 s for ship noise, 11.39 ± 1.48 s for boat noise, 7.21 ± 0.82 s for ocean noise, and 6.66 ± 0.95 s for the silent treatment (Fig. 94.1a). Noise treatment significantly affected predator response latency (ANOVA: $F_{3,55} = 10.7$, $P < 0.0001$); specifically, the mean response latency during the shipping noise treatment was significantly longer compared with the silent control, ambient ocean noise, and boat noise (adjusted $P < 0.0001$, <0.0001, and 0.02, respectively). Hermit crab response latencies to the silent track, natural ocean noise, and boat noise playbacks were not significantly different from each other; however, the variance in response latencies to both noise treatments was noticeably larger than that to the controls.

Noise treatments did not affect the time to emergence ($P = 0.1666$), although the emergence time was longer in both noise treatments than in the controls (Fig. 94.1b)

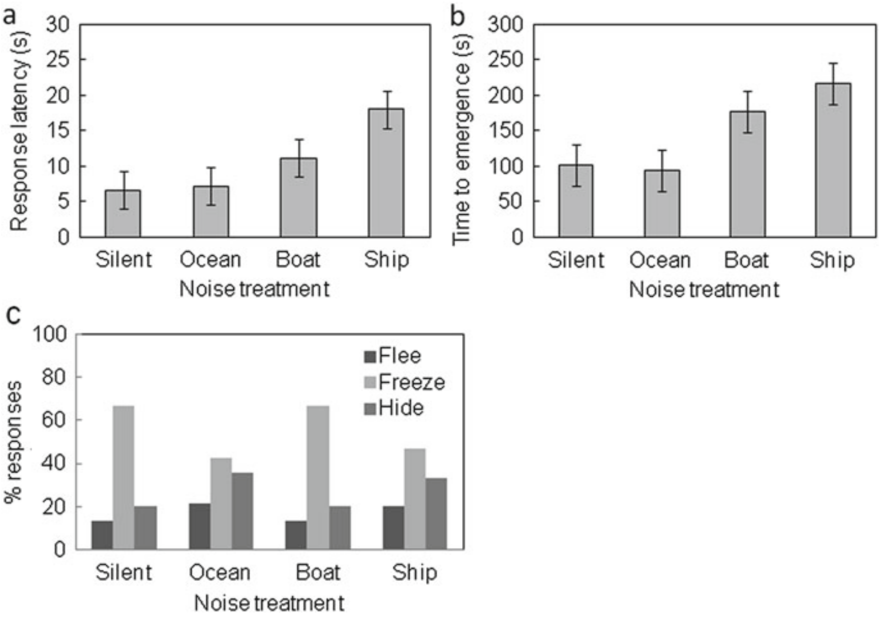

Fig. 94.1 Effect of noise treatment on latency of first antipredator response (**a**), time to emergence (**b**), and latency of response (**c**) by response type in common hermit crabs. Noise treatments were silent control; ambient ocean noise from Glacier Bay, Alaska; variable boat noise from a 150-hp boat traveling at medium speed; and continuous shipping noise from a merchant vessel. Responses were fleeing, freezing in place but not retracting into shell, and hiding in shell

and, similar to the response latency, the emergence time was more variable during noise treatments than during controls. The most frequent first antipredator response type was to freeze (56%), with fewer crabs hiding in their shells (27%) and the fewest fleeing (17%), which did not differ between noise treatment (Fig. 94.1c). No significant association was found between noise treatment and antipredator response type (Fisher's exact test: $P=0.8888$).

No significant correlations were found between the latency of response during each treatment and either hermit crab size (Pearson coefficient: $r_{57}=0.0323$, $P=0.8081$; Fig. 94.2a) or day of trial (Pearson's coefficient: $r_{57}=-0.0958$, $P=0.47$; Fig. 94.2b). However, a significant correlation was found between the duration of noise exposure and latency of the first antipredator response (Pearson's coefficient: $r_{57}=0.263$, $P=0.04$; Fig. 94.2c), so a post hoc ANCOVA was run to determine whether the duration of noise exposure could have accounted for the significant difference in response latency for any of the treatments. From this test, the duration of noise exposure was found to influence the response latency to only a small extent, contributing a sum-of-squares value of 18.96 to the variation, in comparison to the effect of treatment (SS = 1,229.9), which was determined to be nonsignificant ($P=0.49$). The interaction term between duration and treatment also explained some of the variation in response latency (SS = 117.13), but again this was not significant ($P=0.40$).

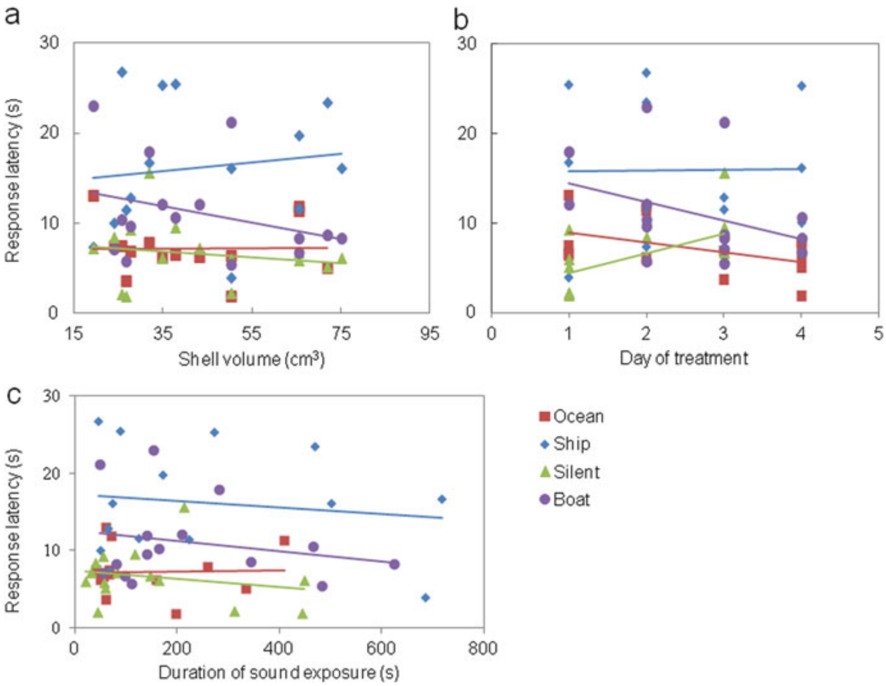

Fig. 94.2 Correlation between latency of first antipredator response and shell volume (**a**), day of testing (**b**), and duration of noise exposure (**c**)

4 Discussion

Hermit crabs took longer to respond to a simulated predator when exposed to shipping-type noise than during exposure to either boat noise, ambient ocean noise, or silence, suggesting that noise could have implications for the survival of individuals in noisy environments. Shipping noise appeared to cause decreased predator vigilance, which under natural conditions could mean that a predator would be able to approach nearer before any evasive response by the hermit crab, which could have fatal consequences, although the type of response does not appear to be affected by noise. These results further support a growing body of evidence that low-frequency anthropogenic noise has indirect effects on the survival and reproduction of both fish and invertebrate species.

Distraction has been proposed as a potential mechanism by which noise can cause decreased predator vigilance in terrestrial hermit crabs (Chan et al. 2010a, b), and the results here demonstrate that noise had a similar effect in the marine environment. Interestingly, the two types of noise treatments elicited response latencies that were significantly different, suggesting that the specific nature of anthropogenic noise did have some influence. This difference could have been related to the intermittent nature of the boat noise, which could make it more unpredictable and cause increased attention rather than distraction. Recreational boating is very popular in the area from which these crabs were collected, with 44% of Scotland's berths being located in the Clyde Estuary (Baxter et al. 2011), whereas commercial shipping is restricted to specific areas farther from the collection area, suggesting the possibility for some amount of prior experience with this noise type. Regardless, the response latency during the boat noise treatment was longer than that in both controls by at least 4 s, suggesting that with more data, this difference may become significant, particularly if the variability in response time to the boat noise treatment was reduced.

Furthermore, these results demonstrate the importance of understanding the effects of all types of noise on all aquatic life. Although they may not have a highly complex sound production/reception system, hermit crabs do appear to be sensitive to noise and could experience population declines as a result. Hermit crabs play several key roles in maintaining healthy ecosystem functioning; in addition to being prey for commercially important species such as *Cancer pagurus* (edible crab) and *Gadus morhua* (Atlantic cod), they are key benthic scavengers, removing considerable amounts of decaying organic matter from coastal areas (Bertness 1981) and ecosystem engineers that provide habitats for a huge amount of biodiversity (Williams and McDermott 2004). Therefore, decreases in hermit crab numbers could have implications within local ecosystems, possibly including altered food web structures or unbalanced nutrient levels through the build-up of decaying matter. More work is needed to isolate the precise parameters that these crabs are responding to, the specific noise characteristics that are most distracting, and the effects of declines in hermit crab abundance, but this work provides one more piece of evidence that increasing amounts of continuous, moderate-intensity noise is a concern for the marine environment.

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Chapter 95
The Use of Deep Water Berths and the Effect of Noise on Bottlenose Dolphins in the Shannon Estuary cSAC

Joanne M. O'Brien, Suzanne Beck, Simon D. Berrow, Michel André, Mike van der Schaar, Ian O'Connor, and Eugene P. McKeown

Abstract The Shannon Estuary on the west coast of Ireland is one of Europe's premier deepwater berths catering for ships up to 200,000 deadweight tonnage. It is also Ireland's only designated candidate special area of conservation for bottlenose dolphins under the EU Habitats Directive. Long-term static acoustic monitoring was carried out at a number of intensive shipping sites. In 2012, noise monitoring took place over a 6-month period (at 1 site) as part of Ireland's requirements under the Marine Strategy Framework Directive (MSFD). This is the first assessment of the potential effect of vessel traffic on the behavior of this discrete dolphin population.

Keywords Noise monitoring • Special area of conservation • Shipping • LIDO • Marine Strategy Framework Directive

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1 Introduction

Ocean noise has always existed in both natural and biological forms, including natural geophysical sounds, precipitation, wave action, lightning, cracking ice, and undersea earthquakes. The dominant source of natural geophysical noise at low frequencies is wave action (National Research Council 2003). This can increase ocean noise levels by more than 20 dB in the 10-Hz to 10-kHz frequency band (Wilson et al. 1985). Biological noise is also emitted into the marine environment from a number of marine taxa. One of the most well-studied and notable biological contributions to marine noise comes from marine mammal vocalizations. These sounds cover a very wide range of frequencies, with dominant components between 20 Hz and 20 kHz (Richardson et al. 1995). Sources of anthropogenic noise that have come under recent scrutiny can include noise emitted from shipping, seismic, and geophysical surveying; construction; drilling and production; dredging; sonar systems; acoustic deterrents; and, more recently, the construction and operation of renewable energy platforms. For assessment purposes, anthropogenic noise sources are often characterized as impulsive if their duration is brief or continuous if the noise source persists for a prolonged time (Richardson et al. 1995). Shipping is a known continuous anthropogenic noise source and has been reported as the dominant source of anthropogenic sound in a broadband range from 5 to 300 Hz (National Research Council 2005), with the main cause of noise being propeller cavitation (Richardson et al. 1995). Characteristics of shipping noise, including frequency and source level, are roughly related to vessel size and speed, although this relationship is further complicated by vessel design and advances in ship technology (Richardson et al. 1995). Anthropogenic ocean noise can elicit a range of physical, physiological, and behavioral effects on the marine fauna.

A number of existing laws relevant to Ireland are in place to assess and mitigate the impacts of anthropogenic noise in the marine environment. The most relevant and recent EU legislation is the Marine Strategy Framework Directive (MSFD). The main aim of the MSFD is that Europe's seas achieve good environmental status (GES) by 2020. Under this directive, member states hope to reach a balance between utilizing the ocean as a natural resource and the ability to achieve and maintain good environmental status for marine waters. A problem faced by conservation actions is a lack of information about the effects of anthropogenic sound on marine species, which will enable member states to determine whether GES has been achieved.

The Shannon Estuary on the west coast of Ireland is an important habitat for *Tursiops truncatus* (bottlenose dolphin). It houses Ireland's only long-term resident group of dolphins and is currently the only designated candidate special area of conservation (cSAC; Lower River Shannon, site code 2165) for this species. Genetic and abundance studies of this population have found that it may be genetically discrete from other coastal dolphins and thus of a very high conservation value (Mirimin et al. 2011). The most recent abundance of estimate in the estuary was 107 individuals (95% CI = 83–131; Berrow et al. 2012).

The Shannon Estuary is also one of Europe's premier deepwater berths catering to ships up to 200,000 deadweight tonnage. It has six main terminals and handles up to 1,000 ships carrying 12 million tons of cargo per annum (Anon 2012). Additionally, a car and passenger ferry operates all year-round between Killimer, County Clare, and Tarbert, County Kerry, and the estuary also has two licensed dolphin-watching vessels operating between April and October. Fishing activity also takes place in the estuary, with potting being the most notable. Additionally, a significant number of pleasure crafts exist year-round in the estuary. Hence, this is an area exposed to high levels of anthropogenic noise from a range of vessel activity. The acoustic signature of a vessel depends on a number of characteristics including gross tonnage, draft, operating equipment, speed, and sea state (McKenna et al. 2012; OSPAR 2012). Small ships tend to be quieter at low frequencies but can approach or exceed noise levels of larger ships at higher frequencies (Hildebrand 2005). Source levels for vessels, in decibels re 1 μPa at 1 m, range from 140 dB for small fishing vessels to 195 dB for super tankers (Hildebrand 2005).

Tursiops truncatus have developed a sonar system whereby they use echolocation to extract information about objects' characteristics directly from returning echoes (Harley et al. 2003). Bottlenose dolphin's echolocation clicks are broadband, with a frequency range of between 200 Hz and 150 kHz, with a peak energy of 30–60 kHz and a source of level between 40 and 80 dB re 1 mbar at 1 m (Evans 1973). Although the noise from shipping is at a lower frequency and more likely to impact on baleen whales, it adds to the ambient noise levels of an area. Behavioral changes by *Tursiops* have been observed worldwide in response to vessel traffic, especially from smaller pleasure craft. Evans et al. (1992) found that pleasure craft traffic had an effect on the dive times of *Tursiops* in Cardigan Bay by avoiding approaching vessels, noting that quieter faster boats caused more disturbance than larger slower moving boats. In the Moray Firth, Hastie et al. (2003) noted increased breathing synchrony between group members in response to heavy boat traffic. While in New Zealand, vertical avoidance of tour boats coupled with an increase in time spent underwater was reported by Lusseau (2003).

Long-term static acoustic monitoring (SAM) of *Tursiops truncatus* in deepwater berths in the estuary has been ongoing under a strategic integrated framework plan (SIFP). This is an interjurisdictional land- and marine-based framework plan to guide the future development and management of the area. A strategic environmental assessment (SEA) and appropriate assessment (AA) were carried out to guide and inform the process. Additionally, to address Ireland's legislative requirements under the MSFD, a long-term (6-months) noise-monitoring network using the LIDO system supplied by Laboratory of Applied Bioacoustics (LAB-UPC, Spain), was deployed at Tarbert Jetty, County Kerry, as part of an EPA-funded program. This program was designed to test noise-monitoring equipment that could be used in Irish waters as part of a monitoring network to be established by 2014. Independent short-term noise measurements were also undertaken by Biopsheric Engineering at two other locations in the estuary. Also during this period, a short-term C-POD deployment was carried out at Tarbert. These two projects coupled together provide a means to generate noise measurements for the estuary and to assess, if any, the effects of vessel presence on dolphin behavior. Here we present the first noise measurements for the Shannon Estuary cSAC and a basic but first assessment on the effects of vessel activity on the resident group of dolphins.

2 Materials and Methods

Between June and September 2012, a noise-monitoring station was installed at Tarbert Jetty, consisting of the LIDO equipment supplied by LAB-UPC (Fig. 95.1). An SMID digital hydrophone was installed at the jetty (~15 m above chart datum), which was connected to an embedded SBC (computer system) that stored the data on a HDD and allowed, through an underwater connector, data transfer via Ethernet. Noise measurement took place in the third-octave bands centered at 63 and 125 Hz as required under the MSFD Indicator 11.2.1 of Descriptor 11; short tonal signals were between 2,500 and 20,000 Hz. Additionally, impulsive signals between 20 and 46 kHz were also monitored for dolphin sonar between 46 and 94 kHz. A real-time data stream was available for the general public at www.listentothedeep.com. An automatic information system (AIS) receiver connected to laptop computer running ShipPlotter was also installed at the jetty. Noise measurements, public data streams, and the AIS data were transferred to the LAB-UPC database server in Vilanova i la Geltru (Spain) over a 3G network connection.

Additionally, Biospheric Engineering made a number of short-duration noise measurements at two locations (Labasheeda Bay and Kilbaha Bay, County Clare). Calibrations were carried out at 250.12 Hz, 500 Hz, 1 kHz, 5 kHz, 10 kHz, and 20 kHz. Calibration was carried out using a Brüel & Kjær type 4,223 hydrophone calibrator and cross checked with a Brüel & Kjær type 2,250 sound level analyzer before and after each set of measurements. All recordings were carried out in 20 m of water.

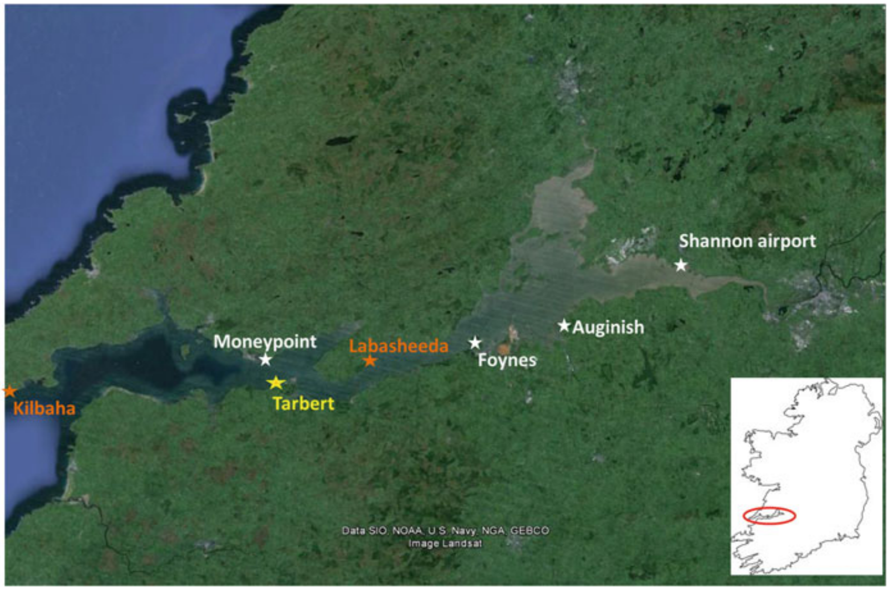

Fig. 95.1 Map of CPOD monitoring stations (*white*), LIDO noise monitoring network location (*yellow*), and Biospheric Engineering noise measurements (*orange*)

Weather conditions at each location were consistent during measurements, with fair weather and winds <10 kt. Deployment at each location involved placing the recording device in a protective cage (converted lobster pot). Data were in the form of 15-min-long WAV files providing a continuous audible record of the noise events. Each file was first analyzed to determine the root-mean-square (rms) noise level every 125 ms. This resulted in 7,200 rms values for each file. These rms values were analyzed in turn to determine the percentile values so that background levels could be isolated from events such as shipping noise.

Long-term SAM of deepwater berths in the Shannon Estuary using C-PODs commenced in 2010 (under the SIFP program) and is currently ongoing. C-PODs are self-contained click detectors that log the echolocation clicks of porpoises and dolphins. Once deployed at sea, the C-POD operates in a passive mode and is constantly listening for tonal clicks within a frequency range of 20–160 kHz. When a tonal click is detected, the C-POD does not record actual sounds but records information about the sounds including time of occurrence, center frequency, intensity, duration, bandwidth, and frequency of the click. Dedicated software (CPOD.exe), provided by the manufacturer, was used to process the data from the SD card when connected to a PC via a card reader. Using the dedicated CPOD.exe software, a train detection algorithm is run through the raw data to produce a CP.3 file. Through this process of train detection, C-PODs record a wide range of click types, but the train detection searches for coherent trains within them. All units were deployed at four deepwater berths from the Moneypoint power station upriver to Shannon Airport, ~80 km from the mouth of the estuary at Loop Head (Fig. 95.1). Lightweight mooring designs were employed during monitoring of each of the sites by attaching them to existing structures, e.g., jetties. A roped line was hung from the top of the jetty with a 20-kg weight attached to the end. At approximately midwater, a loop was etched in the line and the C-POD units were shackled secure. A fifth C-POD was deployed at Tarbert Jetty (June to August) simultaneous to the LIDO deployment, and this afforded the opportunity to assess the difference in dolphin acoustic behavior, if any, in the presence or vessel traffic. Click train properties (including train duration [ms], number of clicks per train, clicks per second, maximum interclick interval [ICI; ms], minimum ICI [ms], and minimum and maximum frequency) were extracted and analyzed to describe dolphin echolocation repertoire in the presence or absence of ships. Statistical analysis was carried out on all trains detected using R (R Development Core Team 2011), and a significance value of $P<0.05$ was used for all analyses. The dataset was found to be nonnormal ($k=12.42$, $P=0.00$); therefore, a Kruskal-Wallis nonparametric test was performed.

3 Results

The Shannon Estuary has a very complicated geometry and bathymetry. Through the LIDO measurements, an attempt was made to characterize the transmission loss in the channel using the received level measurements from ships passing the

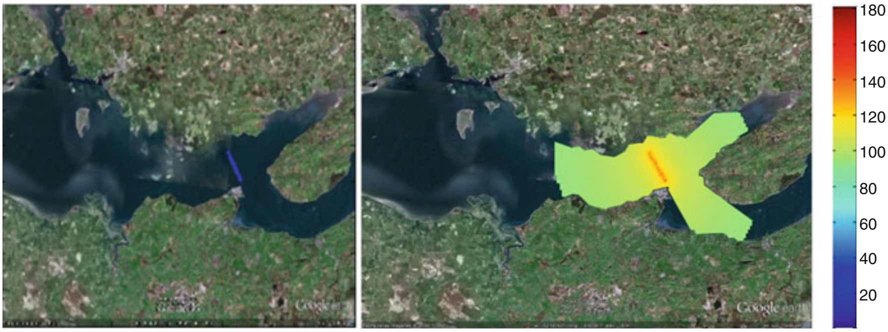

Fig. 95.2 Estimated sound pressure level (SPL) during ferry activities

hydrophone in combination with their positions taken from AIS data. Wide dispersion around the median was evident and most likely due to contributing noise sources (e.g., self-noise) and directivity of the source level at the local ferry. A ferry track consisting of 13 points was computed by averaging all available tracks for the month of September. An omnidirectional source level was taken from the literature where McKenna et al. (2012) list source levels for vehicle carriers of lengths between 173 and 199 m at ~170 dB re 1 μPa at 1 m for the third octave centered on 125 Hz. The ferries operating in the channel were smaller than this so a source level estimate of 160 dB was used. The ferry track and the estimated received sound pressure level of points around the track based on their proximity to the track and a transmission loss of 18 log(R) are shown in Fig. 95.2. From the model, it was expected that the ferry levels should have been measured more clearly, but it was likely that the source level estimation was too high.

To analyze shipping activity, histograms were made averaging the number of received AIS messages over each hour of the day during September 2012. Only movements with a speed over 1 kt were taken into consideration. The Shannon Estuary is a busy shipping area with both transiting and stationary vessels present at all times. On average, four ships transited the Tarbert monitoring station per day. This shipping activity appeared to be concentrated mostly in the mornings and evenings, with especially high activity from Thursday night to Friday morning. Results showed that shipping activity produced noise between 120 and 140 dB for the channel at Tarbert.

Analyses of measurements taken by Biospheric Engineering were made using Avisoft Bioacoustics SASLab Pro and Signal Lab's SigView 32 software packages. From this noise, levels could be divided into three main categories: (1) background noise level (no dominant sound, low noise level); (2) biological noise level (louder sounds not attributable to anthropogenic sources); and (3) shipping noise (louder sounds attributable to shipping traffic). Periods where either shipping noise, biological noise, or background noise was the dominant noise source were isolated. Each period was then analyzed, and a third-octave spectrum for the three main noise source types was prepared. To get a greater understanding of the noise level on a longer term, the rms noise level was plotted for each of the 15-min monitoring periods. Along with the rms value, instantaneous noise levels were evaluated to calculate percentile noise levels. All results were broadband (5 Hz to 20 kHz) rms values. The mean noise level for the Shannon Estuary was calculated at 100 ± 7.5 dB re 1 μPa.

From CPOD data, *Tursiops* were regularly recorded at all of the sites monitored during the long-term SIFP study, ranging from 80 to 21% of days. Detections were recorded, on average, on 47% of days monitored across all sites. Over the 59-day period at Tarbert Jetty, dolphins were recorded on 55% of days. This totaled 614 click trains, which had an average number of 24 clicks/s and an average frequency of 103 kHz. From the AIS and noise data at Tarbert, it was determined if each click train detected was in the presence or absence of vessel activity. Results showed a significantly higher ICI in the presence of vessel activity at the Tarbert site ($\chi^2 = 4.9491$, $P = 0.02$).

4 Discussion

Because cetaceans are reliant on sound for critical survival activities such as navigating, orientation, foraging, and communicating with other group members, it makes them extremely vulnerable to noise disturbance. Clearly, the Shannon Estuary is a busy shipping area, but a variety of other vessel activities exists, including ferries, fishers, tour boats, and pleasure craft. Because these smaller crafts produce noise in the 1- to 50-kHz bracket, it is likely that they pose a higher risk to dolphins in terms of disturbance than lower frequency shipping. A reduction in the communication range of bottlenose dolphins of 26% was estimated within a 50-m radius of small vessels (Jensen et al. 2009). Foraging disruption caused by boat presence has been observed for *Orchinus orca* (killer whales; Williams et al. 2006) and *Delphinus delphis* (common dolphins; Stockin et al. 2008). This can have an effect on the daily life functions of animals and hence impact negatively, such as a reduction in the survival and condition of calves (Lusseau et al. 2006).

The results from SAM show that *Tursiops* regularly use deepwater berths that are the main shipping routes used in the estuary and so will be exposed daily to shipping. Noise-monitoring results show that the estuary is a noisy place (100 ± 7.5 dB) but is marginally quieter in comparison with the results generated by Beck et al. (2013) for Dublin Bay (113 ± 8.2 dB) and Galway Bay (103 ± 4.2 dB). These results are the first estimates of noise levels to be produced for the area and some of the first carried out in Irish waters.

The results presented in this paper are the first attempt to assess if vessel activity has an effect on dolphin behavior in this protected site. Admittedly, this is a crude investigation of the effect of vessel presence at the site but, at present, is our only means of assessment. Although the results show a significant increase in the ICI in the presence of vessels, it is uncertain if this behavioral shift is a negative response as a possible interim mechanism for managing an increase in ambient-noise levels. This study will serve to focus future research in the Shannon Estuary, where simultaneous land-based visual monitoring combined with techniques to describe the whistle repertoire during exposure to a variety of vessel types could provide further insight into the effects of shipping noise. The present study served as a means for Ireland to test noise-monitoring equipment necessary to meet the requirements under MSFD but also assess noise levels in a busy industrial area which is the target of future proposed works such as the development of a liquid nitrogen gas (LNG) terminal and tidal energy. Moneypoint and Tarbert are strategic energy sites and are treated as key strategic drivers of economic growth in the region. The results will serve to inform protocols of best practice for such working areas to ensure that these Annex II species are not impacted negatively.

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Chapter 96
Sound Transmission Validation and Sensitivity Studies in Numerical Models

Steve P. Oberrecht, Petr Krysl, and Ted W. Cranford

Abstract In 1974, Norris and Harvey published an experimental study of sound transmission into the head of the bottlenose dolphin. We used this rare source of data to validate our Vibroacoustic Toolkit, an array of numerical modeling simulation tools. Norris and Harvey provided measurements of received sound pressure in various locations within the dolphin's head from a sound source that was moved around the outside of the head. Our toolkit was used to predict the curves of pressure with the best-guess input data (material properties, transducer and hydrophone locations, and geometry of the animal's head). In addition, we performed a series of sensitivity analyses (SAs). SA is concerned with understanding how input changes to the model influence the outputs. SA can enhance understanding of a complex model by finding and analyzing unexpected model behavior, discriminating which inputs have a dominant effect on particular outputs, exploring how inputs combine to affect outputs, and gaining insight as to what additional information improves the model's ability to predict. Even when a computational model does not adequately reproduce the behavior of a physical system, its sensitivities may be useful for developing inferences about key features of the physical system. Our findings may become a valuable source of information for modeling the interactions between sound and anatomy.

Keywords Acoustic • Dolphin • Simulation • Tissue properties

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1 Introduction

Norris and Harvey (1974) suspended the head of a freshly dead adult *Tursiops truncatus* in seawater and installed an arm 82 cm in length that could be rotated horizontally around the head. A transducer positioned at the end of the arm was used to play sounds that were received by hydrophones implanted in various locations of the carcass. The curves of sound pressure (expressed as measured voltages) are displayed in Norris and Harvey (1974; Fig. 96.1). These measurements represent a rare source of validation data for our vibroacoustic model.

The model used in the present study was described by Krysl et al. (2008). Its basic principle is the superposition of the known incident pressure field and the unknown perturbation pressure field. The software toolkit VATk was used to predict the curves of pressure with the best-guess input data. The inputs include material properties, transducer and hydrophone locations, and the geometry of the animal's head.

2 Methods

Because a good quality computed tomography (CT) scan of a *Tursiops truncatus* was not available to us, we performed our computational experiments using the CT scan of a *Delphinus delphis* (specimen KDX198). The voxel dimensions for the 3-dimensional (3-D) image were 0.625 × 0.625 × 0.625, and the volume consisted of 840 × 461 × 524 voxels.

The geometry of the volume of interest is a block divided into volumetric elements of identical size and shape. The finite-element method is used to discretize the geometry into elements that coincide with the voxels. The dynamic response of the scattered wave is integrated in time with the centered-difference method. The incident wave provides the forcing, and the scattered pressure wave is subject to absorbing boundary conditions at the boundary of the computational volume to

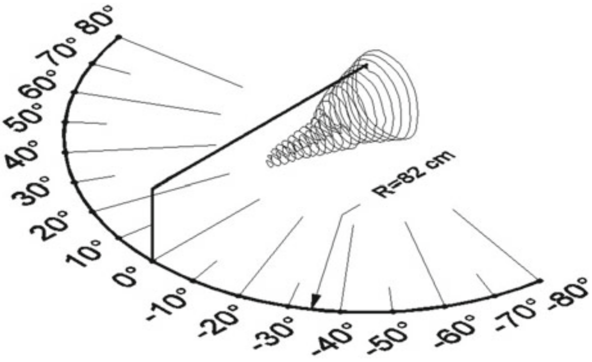

Fig. 96.1 Setup of the Norris and Harvey (1974) study

only allow waves to leave. The absorbing boundary conditions in the present implementation are based on the plane-wave approximation.

For computational expediency, the original CT scan was resampled to reduce the number of voxels. The cubic voxel dimensions for the 3-D image of the model were 2.5 × 2.5 × 2.48 mm. The resampled volume was also padded with voxels having an intensity that corresponds to seawater. This is done to accommodate the transponder locations at the end of the 82-cm-long arm. The computational volume is therefore a 3-D image with dimensions of 485 × 266 × 731 voxels, which are converted to almost cubical finite elements.

Norris and Harvey (1974) reported good data for hydrophones located in the external auditory meatus (1), mandibular fat body anterior to bulla (2), blubber over the pan bone (3S), mandibular fat body (6.8 cm deep; 3D), and Mellon, made lateral (5.3 cm deep; 6). In the original experimental setup, the transducer was moved around the head in unspecified angular increments; unfortunately, the reported curves do not indicate the exact locations of the specific data points used.

In this work, the principle of acoustic reciprocity is key; the receiver and transducer locations were reversed such that in the simulations, the sound "source" was located in one of the five "receiver" locations 1, 2, 3S, 3D, or 6, and the receiver stations were located at the end of the "arm" at 10° increments between −80° and +80°. Here 0° represented the location directly ahead of the animal. The source in the present simulations was a pure tone over a single cycle at 20 kHz. The propagating sound wave was tracked for a sufficiently long time so that the cycle wave passed all of the receiver stations.

For the validation study, we adopted mechanical properties of tissues that have been previously reported in the literature. The mechanical properties used for bone were Young's modulus (modulus of elasticity), $E = 20{,}000$ MPa; Poisson ratio, $\nu = 0.2$; and mass density, $\rho = 2{,}600$ kg/m^3 (Currey 1979). The material properties of the soft tissues were taken from Soldevilla et al. (2005), with the exception of the acoustic fats for which Norris and Harvey (1974) provided the measurements:

- Connective tissue: speed of sound, $c = 1{,}620$ m/s; mass density, $\rho = 1{,}087$ kg/m^3; Young's modulus, $E = 0.124$ MPa.
- Muscle: speed of sound, $c = 1{,}520$ m/s; mass density, $\rho = 993$ kg/m^3; Young's modulus, $E = 0.1$ MPa.
- Blubber: speed of sound $c = 1{,}465$ m/s; mass density, $\rho = 935$ kg/m^3; Young's modulus, $E = 0.065$ MPa.
- Acoustic fats: following Norris and Harvey (1974), we used four classes of acoustic fat with a graduated speed of sound, $c = 1{,}450$, 1,430, 1,370, and 1,340 m/s, all with mass density $\rho = 937$ kg/m^3 and Young's modulus $E = 0.065$ MPa.

The properties of seawater were taken as $\rho_w = 1{,}000$ kg/m^3 and $c_w = 1{,}500$ m/s.

In the sensitivity analysis, we varied the properties of tissues systematically. Young's modulus, of the four independent material properties listed above, were varied by several orders of magnitude while holding the bulk modulus constant. The bulk modulus of the four independent properties was varied over a broad range for the meatus (1) location to estimate the best sensitivity range for global comparisons.

The bulk modulus of the four independent properties was subsequently adjusted by ±4% at each of the listed hydrophone locations (1, 2, 3S, 3D, and 6) to provide sensitivity comparison curves. And finally, the viscosities of the four independent properties were considered by introducing a unity loss tangent for each of the listed hydrophone locations.

Comparisons were based on the correlation of the simulated curves with the published experimental data of the Norris and Harvey (1974) study. The pressure amplitudes were compared across the given ranges of the incident ensonificiation angle. Because the information provided in the aforementioned study is based on instrumentation voltage values, with undetermined pressure field calibrations, the curves were normalized. Qualitative comparisons were drawn by considering the standard correlation coefficients and coefficients of determination.

3 Results

The simulations faithfully reproduced the qualitative behavior of the experimental data presented in the Norris and Harvey (1974) study, with particularly close agreement in the anterior bulla left region where the predicted angle of maximum acoustic response was a very close match (Fig. 96.2). In certain datasets, both the fit and general shapes of the curves were improved if Young's modulus of the

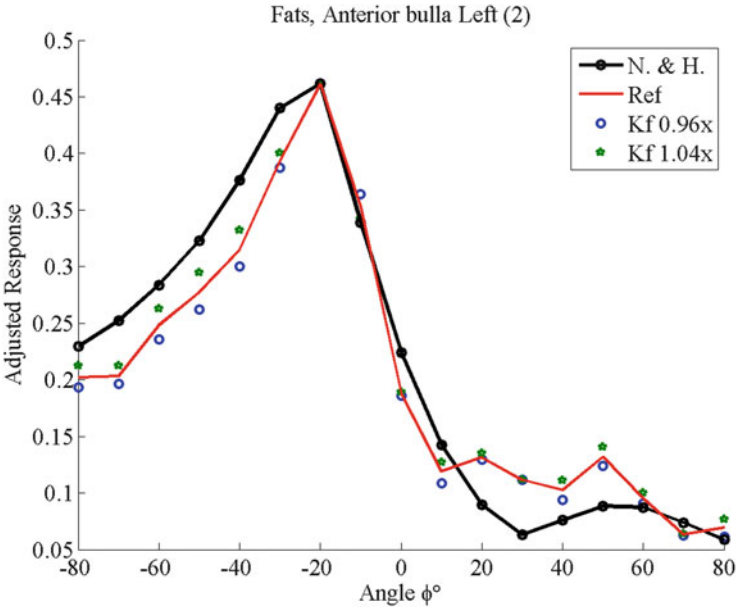

Fig. 96.2 Simulation curves plotted against experimental results for the second dataset (anterior bulla left)

bone was reduced to 50% of its assumed value found in the literature. It is plausible that the porosity of the bone causes its macroscopic structural behavior to appear less rigid than materials testing at a local scale would suggest. This would account for the improved fit when the assumed value of Young's modulus is reduced.

Although changes in Young's modulus of the bone outweighed changes in the elastic properties of the soft tissues, altering the bulk modulus of the soft tissues still had an appreciable effect. Among the soft tissues considered, estimations of the bulk modulus of the acoustic fats had the most influence on the simulated pressure fields. Including the additional consideration of viscosity in the soft tissues, however, did not affect the solutions to the extent that the viscosity of the bone did.

Changing the bulk modulus of the fats fostered a significant change in the resulting pressure magnitudes for eight of ten configurations and showed the greatest sensitivity for four of five datasets tested. Including viscosity gave appreciable changes in the outputs only when the viscosity was applied to the bone. Inclusion of bone viscosity produced changes in the resulting pressure fields for five of five datasets. Of the hydrophone configurations tested, simulations of dataset 2 (anterior bulla left) provided the best fit when using the reference material properties.

The qualitative match among the simulation and experimental results were improved slightly by increasing the viscosity of bone and the bulk modulus of the acoustic fats. Agreement of the shapes of the curves, taken by comparing the locations of local maxima and minima, was substantially improved by reducing Young's modulus of the bone by 50% for datasets 1, 3S, 3D, and 6.

The angle of maximum pressure determined from the simulations fit the experimental data with a rather large margin of ±30°. The predicted angle of the maximum signal matched the experimental results in the second dataset (anterior bulla left). The overall shapes of all the curves were a reasonable match to those of the experimental results.

Acknowledgments This work was funded by the Office of Naval Research (M. Weise).

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Chapter 97
Patterns of Occurrence and Marine Mammal Acoustic Behavior in Relation to Navy Sonar Activity Off Jacksonville, Florida

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Abstract Passive acoustic data collected from marine autonomous recording units deployed off Jacksonville, FL (from 13 September to 8 October 2009 and 3 December 2009 to 8 January 2010), were analyzed for detection of cetaceans and Navy sonar. Cetaceans detected included *Balaenoptera acutorostrata*, *Eubalaena glacialis*, *B. borealis*, *Physeter macrocephalus*, blackfish, and delphinids. *E. glacialis* were detected at shallow and, somewhat unexpectedly, deep sites. *P. macrocephalus* were characterized by a strong diel pattern. *B. acutorostrata* showed the strongest relationship between sonar activity and vocal behavior. These results provide a preliminary assessment of cetacean occurrence off Jacksonville and new insights on vocal responses to sonar.

Keywords Autonomous acoustic recorder • Marine acoustic recording unit • Midfrequency active sonar • Vocal behavior

1 Introduction

Passive acoustic monitoring using autonomous acoustic recorders deployed on the seafloor is an effective method for long-term monitoring of cetaceans (Mellinger et al. 2007). Autonomous acoustic recorders have been used to investigate the

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distribution, abundance, and acoustic behaviors of a variety of cetaceans in diverse habitats and in extreme or remote environments (e.g., Clark et al. 2002; Širović et al. 2004; Johnston et al. 2008). In the fall and winter of 2009–2010, the US Navy (Naval Facilities Engineering Command [NAVFAC] Atlantic) deployed nine marine acoustic recording units (MARUs) off Jacksonville, FL, in the US Navy's Jacksonville (JAX) range complex. The MARU deployments were timed to include antisubmarine warfare (ASW) training exercises. This provided a unique opportunity to examine cetacean vocal activity before, during, and after US Navy midfrequency active sonar (MFAS) events.

We present the results of a detailed qualitative analysis of passive acoustic data collected during these MARU deployments, including the occurrence of cetacean vocalizations and Navy sonar. We characterize spatial and temporal patterns in cetacean vocal activity as well as document vocal behavior in relation to sonar events. This analysis provides new insights as to which species may be sensitive to Navy sonar and recommendations for future research.

2 Methods

2.1 Deployments

Nine MARUs were deployed from 13 September to 8 October 2009 (fall) and from 3 December 2009 to 8 January 2010 (winter), ~60 to 150 km offshore from Jacksonville, FL (Fig. 97.1). The deployment area was located in the US Navy's JAX range complex, in an area that coincides with the planned undersea warfare training range (USWTR). MARUs were deployed in three depth ranges: on the shelf (44–46 m; "shallow sites"), just beyond the shelf (~183 m; "middepth sites"), and offshore from the shelf break (~305 m; "deep sites"). Three recorders were deployed at each of the three depth ranges, for a total of nine MARUs in each deployment. Two types of MARUs were deployed: units that recorded using a 32-kHz sampling rate and units that recorded using a 2-kHz sampling rate. The 32-kHz recorders were deployed at six sites and the 2-kHz recorders were deployed at three sites (Fig. 97.1).

2.2 Data Analysis

Triton software was used to create long-term spectral averages (LTSAs) for all data. Once the LTSAs were created, all biological sounds and Navy sonar events were logged by trained bioacoustic analysts. The unit of analysis was an "acoustic event," defined as any period containing cetacean sounds with <10 min of silence between individual sounds. Acoustic events were identified as to species or the highest taxonomic group (e.g., delphinids and blackfish) possible. "Blackfish" consisted of *Peponocephala*

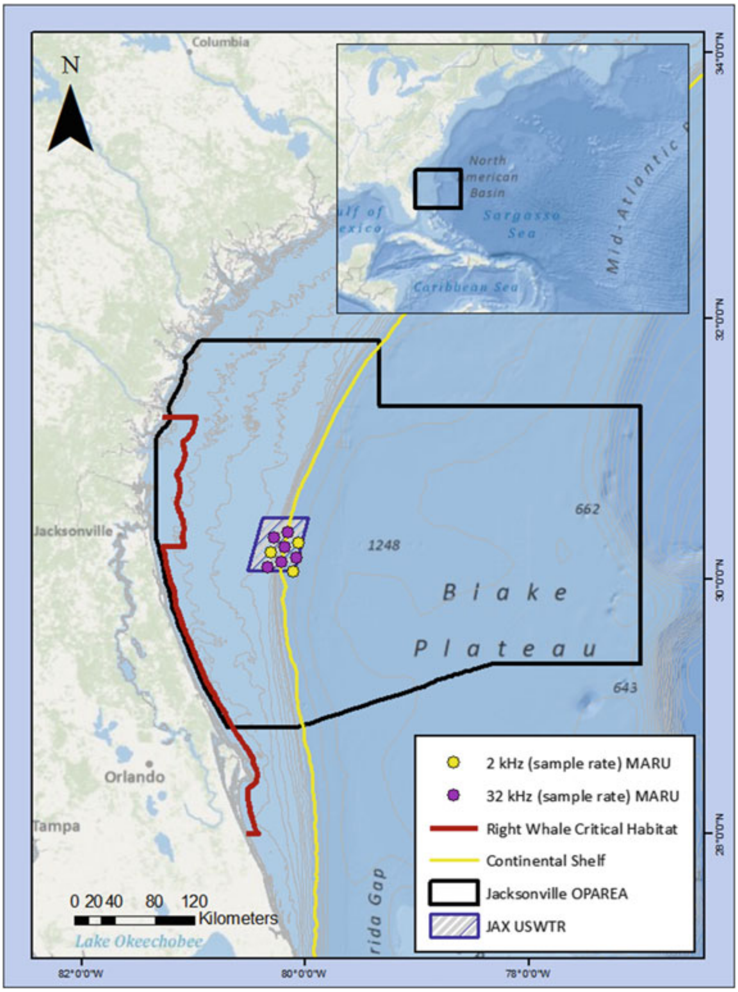

Fig. 97.1 Locations of the marine acoustic recording units (MARUs) deployed in fall and winter 2009–2010 in the planned Jacksonville (JAX) undersea warfare training range (USWTR). *OPAREA* area of operation

electra (melon-headed whales), *Feresa attenuata* (pygmy killer whales), *Pseudorca crassidens* (false killer whales), *Orcinus orca* (killer whales), and *Globicephala macrorhynchus* (short-finned pilot whales). "Delphinids" consisted of all delphinid species other than the blackfish. Blackfish were identified based on the presence of distinctive pulsed sounds as well as low-frequency whistles (2–8 kHz) with few inflection points (Oswald et al. 2004). Blackfish were identified conservatively, and if there was any doubt, the event was labeled as delphinid.

3 Results

3.1 Acoustic Recordings

The 32-kHz units recorded for ~21 days during both fall and winter (13 September to 4 October and 4 December to 26 December, respectively). The 2-kHz units recorded for 25 and 33 days during fall and winter (13 September to 8 October and 5 December to 8 January, respectively). A total of 10,132 h of 2-kHz data and 5,988 h of 32-kHz data were reviewed and analyzed.

3.2 Species Detected

A number of marine mammal species were detected acoustically during both deployments. The species detected as well as the total duration of their acoustic events for each deployment are summarized in Table 97.1. MFAS activity occurred during both deployments but was much more prevalent in the fall deployment than in the winter deployment (535 vs. 99 h, respectively; Fig. 97.2; Table 97.1).

Baleen Whale Detections

Balaenoptera acutorostrata (minke whale) sounds were not detected during the fall deployment but were detected nearly continuously in the winter deployment, representing the highest overall event duration of all species/species groups (1,429 h; Table 97.1). Vocalizations from *B. acutorostrata* were detected predominantly at deep sites and infrequently at shallow sites. Vocal activity was greatly reduced or, in some cases, completely absent during most days with concurrent sonar events (Fig. 97.2a).

Two other baleen whales were detected in the MARU recordings, although not as often as *B. acutorostrata*. Both *Balaenoptera borealis* (sei whales) and *Eubalaena glacialis* (right whales) were detected on recorders at all depths but had low overall event durations (Table 97.1). *E. glacialis* was detected at all sites during both

Table 97.1 Total duration of acoustic events by species

	Fall	Winter	Overall
Blackfish	2 h 17 min 7 s	6 h 35 min 15 s	8 h 52 min 22 s
Delphinid species	301 h 57 min 01 s	235 h 18 min 16 s	537 h 15 min 17 s
Balaenoptera acutorostrata		1,429 h 4 min 4 s	1,429 h 4 min 4 s
Physeter macrocephalus	297 h 29 min 41 s	395 h 10 min 54 s	692 h 40 min 35 s
Eubalaena glacialis	8 h 35 min 33 s	2 h 54 min 43 s	11 h 30 min 16 s
Balaenoptera borealis		8 h 47 min 26 s	8 h 47 min 26 s
MFAS	535 h 24 min 51 s	99 h 1 min 7 s	634 h 7 min 57 s

MFAS midfrequency active sonar

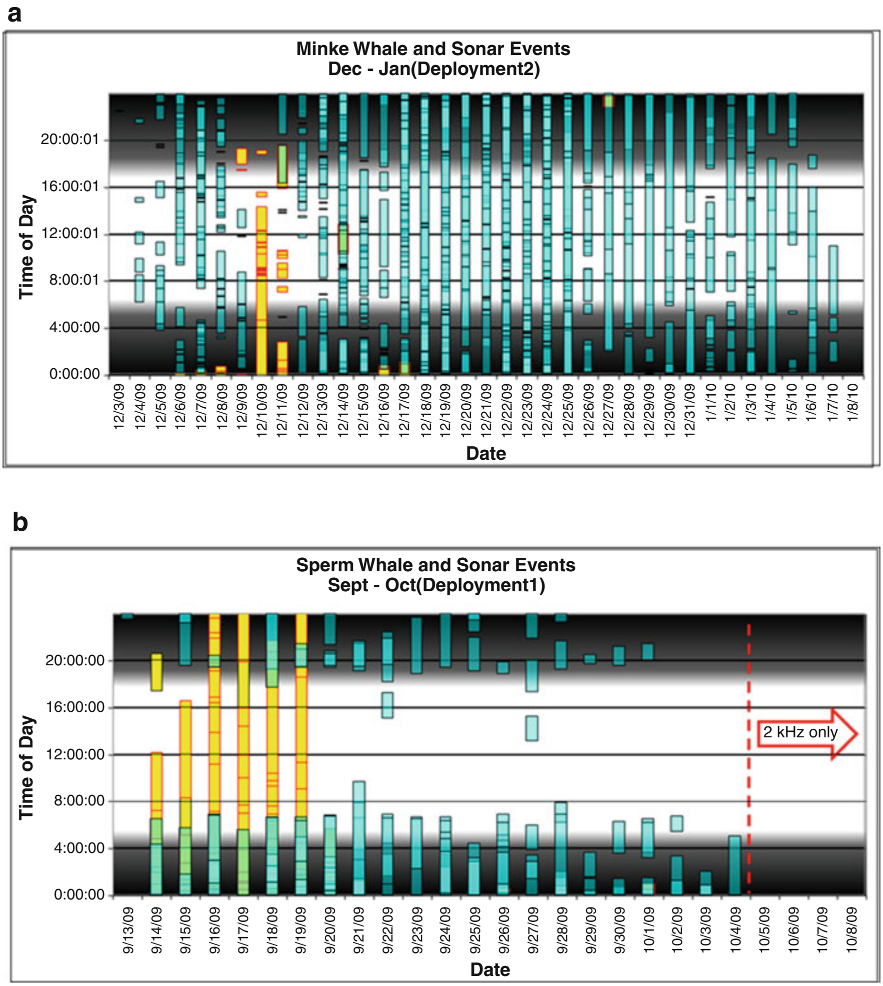

Fig. 97.2 Vocal events (*teal*) and sonar events (*yellow*) by day and time for all nine MARUs combined for *Balaenoptera acutorostrata* during winter deployment (**a**) and *Physeter microcephalus* during fall deployment (**b**). Shading is representative of event overlap, i.e., an event occurring at multiple MARUs. *White* is average daylight and *black* is nighttime for the deployment periods

deployments but was slightly more common during the winter, whereas *B. borealis* was detected during the winter only.

Odontocete Detections

Delphinid species and *Physeter macrocephalus* (sperm whales) were the most commonly detected species during the fall deployment and second and third most commonly detected species during the winter, respectively (Table 97.1). *P. macrocephalus* vocalizations were only detected on the 32-kHz units because energy in their clicks generally does not extend below 1 kHz (the upper recording bandwidth of the 2-kHz sites). Despite the fact that only six of the nine sites included 32-kHz recorders, *P. macrocephalus* was detected every day during the fall and on all but 2 days during the winter. *P. macrocephalus* was detected only at middepth sites during both deployments. Their acoustic events showed a strong diel pattern, occurring predominantly between sunset and sunrise (Fig. 97.2b).

Both delphinid and blackfish species were detected every day and at all 32-kHz sites for both deployment periods. Although some components of the sounds produced by these species can extend below 1 kHz, it was not possible to identify these two species groups based on the limited bandwidth recordings of the 2-kHz data. There were no obvious or consistent differences in the occurrence of delphinid or blackfish vocalizations relative to site depth or time of day.

4 Discussion

Analysis of the JAX MARU deployments provides information about the spatial, seasonal, and diel occurrence patterns for several species and species groups based on their vocal behaviors in an important area for naval activity. When interpreting these results, it should be noted that an absence of vocalizations does not necessarily mean an absence of animals because vocalizing is not an obligatory behavior for most species. Also, for species that produce loud, low-frequency signals (e.g., baleen whales), some sound types may propagate far enough to be detected by several recorders (i.e., at different sites), which may complicate interpretation of occurrence patterns. Despite these constraints, these data provide a more detailed picture of cetacean occurrence than was available for this region based on existing datasets. For example, visual survey data indicate that few *B. borealis*, *P. macrocephalus*, and *E. glacialis* are expected in the JAX USWTR study area (Department of the Navy 2008, 2013). However, *P. macrocephalus* was one of the most commonly detected species in the MARU recordings and *B. borealis* and *E. glacialis* were also more common than expected.

In addition to being detected on the MARU buoys when very few have been recorded to date via visual monitoring (Department of the Navy 2013), *E. glacialis* was also detected in deeper waters than expected. Sightings of *E. glacialis* generally have been concentrated in continental shelf waters offshore from northeastern Florida and southeastern Georgia (e.g., Department of the Navy 2008). Based on the MARU data, it seems that the distribution of this species extends further offshore than sighting data previously indicated. Alternatively, it is possible that propagation of these vocalizations allows them to be detected at long distances and that at least some vocalizations produced in nearshore waters were being recorded by offshore MARUs. Acoustic propagation modeling should be conducted to investigate this possibility.

Both *B. borealis* and *B. acutorostrata* were detected only during the winter deployment. This suggests a seasonal component to the calling behavior and/or migration patterns of these species. *B. acutorostrata* are believed to migrate south to the Caribbean and other areas in the winter and spring (Mitchell 1991). Information about seasonal peaks in detection of *B. acutorostrata* at other recording sites along the US Atlantic coast are needed to fill in the gaps in the knowledge of their migration patterns. The high prevalence of calling events for almost the entire winter deployment indicates a continuous presence of this species during that time period. Further research is necessary to determine whether the animals are continuously migrating through the study area or if the animals are resident during this time period.

In addition to providing information on the spatial occurrence of species, analysis of these data has also highlighted temporal variability in vocal behavior. For example, *P. macrocephalus* exhibited a strong diel pattern, with vocalizations occurring almost exclusively at night. *P. macrocephalus* produce clicks during foraging dives and are generally quiet at the surface (Whitehead 2003; Miller et al. 2008). As such, the diel vocal pattern suggests that this species is spending more time at depth, likely foraging, during the nighttime in this study area. Aoki et al. (2007) and Whitehead (2003) both reported diel patterns in sperm whale dive records and acoustic observations collected around Japan and the Galapagos Islands, respectively. They suggested that these patterns were related to diel vertical migration of prey species. It is important to note that the lack of acoustic detection during the day does not necessarily indicate absence of the species. The animals may stay in the area throughout the day but remain quiet. This option is unlikely, however, because there are few visual records of sperm whales occurring in this area during the daytime. Visual surveys combined with 24-h acoustic tracking and satellite tagging of *P. macrocephalus* can be used to answer these questions.

Based on our qualitative analysis, *B. acutorostrata* was the only species to exhibit an obvious change in calling patterns associated with sonar events. This species called almost continuously during the winter deployment but greatly reduced or stopped calling during sonar events. This indicates either a cessation of calling or movement out of the area. McCarthy et al. (2011) found that beaked whales both reduced their vocal activity and moved away from sonar sources in the Atlantic Undersea Test and Evaluation Center (AUTEC) range in the Bahamas. Recent playbacks of sonar to a *B. acutorostrata* tagged with a radio transmitter and time-depth recorder indicated strong horizontal and vertical responses to sonar (Kvadsheim et al. 2011). Additional research is needed to determine if similar behavioral responses were occurring during the MARU deployments.

Neither diel patterns nor changes in vocal behavior in association with Navy sonar were evident in delphinids or blackfish. These patterns may exist for some species but, if so, they were likely masked by the fact that up to 15 delphinid species and 5 blackfish species were combined into two categories for analysis. Combining many species may result in species-specific patterns being missed or confounded. For example, if one species produces more sounds during the day and another produces more sounds during the night, these two patterns would effectively cancel each other out and make it appear as though calling was continuous, with no diel variation.

Because of the high variability in delphinid vocalizations and the overlap in time, frequency, and spectral characteristics among multiple species, classifying delphinid sounds to the species level would require a more detailed analysis, which was beyond the scope of this project. We are currently developing classifiers to identify whistles from several species of Atlantic dolphins and will apply these classifiers to the JAX MARU dataset. This will allow a more detailed analysis of species-specific vocalization patterns and possible responses to sonar. We are also collaborating with expert bioacousticians to develop a statistical framework for assessing species-specific vocal responses to sonar.

The analysis of autonomous recorder data from MARUs deployed concurrently with naval sonar exercises provided a unique opportunity to examine relationships between vocal behavior and sonar activity. Additionally, these data provided the opportunity to assess species presence as well as spatial and temporal patterns of vocal activity in the region. These types of information are important for developing monitoring and mitigation plans for these federally protected living marine resources.

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Chapter 98
Hearing in Whales and Dolphins: Relevance and Limitations

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Abstract Understanding the hearing of marine mammals has been a priority to quantify and mitigate the impact of anthropogenic sound on these apex predators. Yet our knowledge of cetacean hearing is still limited to a few dozen species, therefore compromising any attempt to design adaptive management strategies. The use of auditory evoked potentials allows scientists to rapidly and noninvasively obtain the hearing data of species rarely available in captivity. Unfortunately, many practical and ethical reasons still limit the availability of large whales, thus restricting the possibility to effectively ensure that anthropogenic sounds have minimum effects on these species. The example of a recent Blainville's beaked whale (*Mesoplodon densirostris*) audiogram collected after a stranding indicated, for instance, very specialized hearing between 40 and 50 kHz, which corresponded to the frequency-modulated upsweep signals used by this species during echolocation. The methods used during a stranding event are presented along with the major difficulties that have slowed down the scientific community in measuring the audition of large whales and the potential value in obtaining such results when successful.

Keywords Cetacean • Audition • Auditory evoked potential

1 Introduction

Quantifying the impact of anthropogenic noise on marine ecosystems remains difficult on a global scale. Apex predators such as cetaceans are known to have evolved advanced hearing mechanisms to process sounds in their environment. Cetacean strandings have been linked to the use of man-made sounds, triggering important efforts to mitigate their effects on dolphins and whales (Nowacek et al. 2007). To effectively reduce the effects of anthropogenic noise on cetaceans, one should

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first examine the basic hearing of these animals. Hearing research is still being conducted regularly, yet it yields a very limited number of audiograms. To date, we only have audiograms of 17 of the 85 species of whales and dolphins, which makes adaptive management decisions and regulations very difficult. To obtain audiograms of new species, scientists have relied on platforms of opportunities such as marine parks, stranding events, or rehabilitation facilities to test the hearing of new species. Yet the opportunities and the feasibility of such research are often limited. This chapter provides an overview of the current noninvasive methods used to obtain the hearing of new species. It also discusses the limitations as well as the technological improvements necessary to measure the hearing of mysticetes.

2 Methods

Common behavioral auditory tests are rarely feasible with stranded or rehabilitated animals. This technique, although very reliable, requires extensive training and data collection can take several months to a year to be completed (Yuen et al. 2005). As an alternative, the use of auditory evoked potentials (AEPs) allows researchers to rapidly obtain audiograms and only requires several hours to complete. The basic principles rely on measuring the voltages generated by the brain in response to acoustic stimulation (Popov and Supin 2007). Many systems have been designed to be portable and user friendly. Such systems are described in detail by Taylor et al. (2007), Finneran (2009), and Pacini et al. (2012). The brain response is usually picked up and recorded via gold electrodes embedded in suction cups. Two to three suction cups are used and are usually positioned by the blowhole to pick up the brain response on the back of the animal to serve as a reference and on the dorsal or other part of the body to act as a ground. The brain response is on the order of several microvolts and has to be amplified several thousand times. To obtain a clear signal, the response to a several-millisecond-long signal is averaged up to 1,000 times (Popov and Supin 2007).

Acoustic stimulation can vary from short broadband clicks, usually used to investigate the temporal resolution of hearing or modulation rate transfer function (MRTF; Mooney et al. 2009) to tone pips and amplitude-modulated tones (Supin and Popov 2007; Nachtigall et al. 2008; Li et al. 2012; Pacini et al. 2012).

The stranding of a Blainville's beaked whale (*Mesoplodon densirostris*) is used as an example. The animal stranded in the morning on the island of Maui on 16 August and was transported to the Hilo Cetacean Rehabilitation Center on the Big Island that same afternoon. The hearing measurements started late at night that same day and were conducted intermittently between veterinary care and feedings (Fig. 98.1). During the measurements, volunteers held the animal at the surface while the hydrophone was kept 2 m in front of the subject. Even though the subject never showed any signs of stress during the measurements, sessions were kept to a maximum of 20 min to ensure minimum interference with the medical treatment. More details about the methods of this particular case are available in Pacini et al. (2011).

Fig. 98.1 Taking Blainville's beaked whale hearing measurements during rehabilitation. See Section 2 for details

3 Results

During a stranding or with an untrained animal, the availability of the animal is often the main limiting factor and the results obtained from such a platform of opportunity can include MRTFs and audiograms. The main results of the Blainville's beaked whale are presented in Pacini et al. (2011), and the best hearing was found between 40 and 50 kHz, which overlapped with the frequency spectrum of the echolocation clicks produced by this species (Johnson et al. 2006). This audiogram differs significantly from the well-known bottlenose dolphin (*Tursiops truncatus*) audiogram, which is often used by management agencies to model zones of ensonification for cetaceans when anthropogenic sounds are a concern because limited data are available for other species.

Some of the more recent audiograms have been obtained through platforms of opportunity such as strandings and rehabilitation facilities. These audiograms include species of concern such as pilot whales (Pacini et al. 2010; Schlundt et al. 2011), Gervais and Blainville's beaked whales (Cook et al. 2006; Pacini et al. 2011), and pygmy sperm whales (Montie et al. 2011). These species' audiograms are of particular importance because the animals are commonly found to strand after the use of active sonar and tend to show that hearing ranges vary with species and that these differences must be taken into account to ensure the best management strategies.

4 Problems and Limitations

The fact that audiograms are currently available for only 17 of the 85 cetacean species is the main evidence of the numerous difficulties researchers encounter while trying to measure basic cetacean hearing. Yet the need to obtain the hearing of new species is evident when interspecific hearing differences are likely to occur.

In addition to obtaining more species, a major issue encountered when testing the hearing of a new species is to extrapolate to a population or species level based on one individual. The example of pilot whales, where the first audiogram showed low-frequency hearing in a young animal, was not confirmed as representative of this species until other audiograms showed similar trends with animals of various ages and sex (Pacini et al. 2010; Schlundt et al. 2011).

To go back to our example of the Blainville's beaked whale audiogram, to date, no other audiogram of this species is available; thus one can question how representative this audiogram is. Yet another beaked whale audiogram is available for a different species (Cook et al. 2006), and even though both the species and methods were different, the shape of the audiogram also indicates very sharp hearing within a narrow frequency range, thus demonstrating a potential acoustic adaptation. If, indeed, hearing range varies with species as an adaptation to their habitat use and foraging ecology, then one should account for these variations when designing conservation strategies to mitigate the effects of anthropogenic noise on marine mammals.

As a physiological measurement, hearing can vary greatly with factors such as age, medical history, or disease, particularly in the case of stranded animals. Houser et al. (2008) showed differences in hearing abilities in a population of *Tursiops truncatus gilli* primarily due to age. Similarly, the two Risso's dolphin audiograms show a clear loss of high hearing with age (Nachtigall et al. 1995, 2005). Finally, the use of ototoxic medications is also known to potentially cause hearing loss (Finneran et al. 2005).

Additional differences can emerge due to differences in technique, positioning of sound presentation, or the ambient noise where the measurements are conducted. Supin and Popov (2007) showed that the use of short tone pips yielded responses at lower intensities than amplitude-modulated tones, thus providing a more accurate threshold. Presenting the acoustic stimulus in the free field as opposed to directly on the panbone of the subject also yields differences in threshold estimation, primarily due to the fact that in the second method, only one ear is stimulated, thus yielding a smaller response (Finneran and Houser 2006).

Although it is difficult to account for all these differences, these data represent the first steps toward an adaptive management strategy to effectively protect species at risk. Because species of concern such as black fish (pilot whales, false killer whales, melon-headed whales, and pygmy killer whales) and beaked whales (known to strand after the use of man-made sonar) are not readily available, obtaining hearing measurements of these species remains a priority (National Research Council 2003, 2005).

Unfortunately, even if these species become available to the research community via a platform of opportunity, regulations and ethical concerns are also a major issue. Under the US Marine Mammal Protection Act in 1972, a permit is required to perform these measurements within the United States. Several countries have similar regulations that limit access to the animals. Additionally, in the situation of a stranding, the animal is usually in distress and its rehabilitation focuses primarily on medical diagnostics and treatment. Although hearing measurements are a medical diagnostic tool, it might not represent a priority to the veterinarians unless there are suspicions that the stranding was related to noise exposure.

Finally, a major issue, particularly in the case of mysticetes and large whales, is the feasibility. To perform a hearing test, the animal has to be in a relatively controlled environment and there are few facilities or spaces capable of rehabilitating a large animal such as a baleen whale. Hearing measurements on large whale calves have been attempted both during a stranding (Nachtigall et al. 2007) and during the long-term rehabilitation of a gray whale (Ridgway and Carder 2001). In both examples, access to the animals as well as to technical issues limited the amount of data that was collected.

5 Advances in Technology

Although these studies depend on platforms of opportunity, continuous improvements in technique and equipment help to maximize every opportunity. For instance, recent improvements in testing low frequencies have been achieved using short tone pips, which are known to elicit a better response than commonly used sinusoidally amplitude-modulated tones and are currently being validated with behavioral tests (Smith, personal communication). These low-frequency measurements assist us in considering procedures for mysticetes that are assumed to hear better in the low-frequency domain.

Because odontocetes rely on echolocation, their brain is highly adapted to acoustic processes and a third of their brain is dedicated to sound. Yet in mysticetes, this pattern is not as clear; thus the use of suction cups might not yield a clear response. Subdermal needle electrodes are commonly used with other mammalian species as well as with humans (Kileny 1991). Designing such needles for mysticetes, for instance, requires the ability to account for blubber thickness and animal size so that only the tip of the needle, positioned on the surface of the skull, picks up voltages while the rest of the needle is fully insulated.

Understanding where to position the recording electrode has also been facilitated with the use of 3-dimentsional (3-D) medical imaging where researchers now have a better view of the animal's anatomy. The use of 3-D imaging as a modeling tool to understand hearing is also being currently validated with empirical data and could potentially lead to a better understanding of hearing without actually testing the animal's hearing directly (Parks et al. 2007; Cranford et al. 2008).

Finally, the AEP systems have been improved over the years to be more and more user friendly to be operated by nonscientists to collect the maximum of data in the limited amount of time allocated to hearing measurements.

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Chapter 99
Humans, Fish, and Whales: How Right Whales Modify Calling Behavior in Response to Shifting Background Noise Conditions

Susan E. Parks, Karina Groch, Paulo Flores, Renata Sousa-Lima, and Ildar R. Urazghildiiev

Abstract This study investigates the role of behavioral plasticity in the variation of sound production of southern right whales (*Eubalaena australis*) in response to changes in the ambient background noise conditions. Data were collected from southern right whales in Brazilian waters in October and November 2011. The goal of this study was to quantify differences in right whale vocalizations recorded in low background noise as a control, fish chorus noise, and vessel noise. Variation in call parameters were detected among the three background noise conditions and have implications for future studies of noise effects on whale sound production.

Keywords Right whale • *Eubalaena australis* • Noise • Vocal modification

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1 Introduction

A "stereotyped" call produced by right whales, the upcall or contact call, is often used for detection in passive acoustic monitoring situations (Van Parijs et al. 2009). Previous studies of the sound production behavior of right whales indicate a variation in the average frequency range and bandwidth of upcalls. This variation has been documented both between and within species, with individual whales modifying their calls in response to noise from vessels (Parks et al. 2007, 2009, 2011).

Currently, there are three recognized species of right whales: the North Atlantic right whale (*Eubalaena glacialis*), the North Pacific right whale (*Eubalaena japonica*), and the southern right whale (*Eubalaena australis*). Both northern hemisphere species are highly endangered, with population estimates at 509 (*E. glacialis*) and 35 (*E. japonica*; Wade et al. 2011; Pettis 2012). The southern right whale has a significantly larger population, with a total estimated population in 2009 of 12,000 individuals (International Whaling Commission 2012). This population has a circumpolar distribution in the southern hemisphere, with primary calving grounds located in Argentina, Brazil, South Africa, Australia, and New Zealand (International Whaling Commission 2012). In one calving area for this population in Brazilian waters, increasing numbers of right whales have been sighted over the past decade along with an increase in anthropogenic activities such as shipping and fishing (Groch et al. 2005). This study investigated the role of behavioral plasticity in the sound production of southern right whales (*Eubalaena australis*) in response to changes in ambient background noise conditions.

2 Methods

Bottom-mounted archival acoustic recorders (DSG-Ocean, Loggerhead Instruments) were deployed in October and November 2011 in two coastal locations in central Santa Catarina State, southern Brazil. One recorder was placed off Gamboa Beach (27°56′ S, 48°39′ W) and one off Ribanceira Beach (28°11′ S, 48°37′ W). Acoustic recordings were manually browsed to identify periods dominated by three different background noise conditions: (1) fish chorus, (2) vessel noise, and (3) neither/control (Fig. 99.1). Automated detectors and noise statistic analysis tools developed for North Atlantic right whale upcalls were utilized to analyze recordings from each of these conditions (described in Urazghildiiev and Clark 2006; Parks et al. 2009; Urazghildiiev et al. 2009).

3 Results

The acoustic recorders were deployed for 14 days off Gamboa and for 22 days off Ribanceira. Right whales were regularly sighted in both locations. Over 10,000 right whale calls were automatically detected between the two locations.

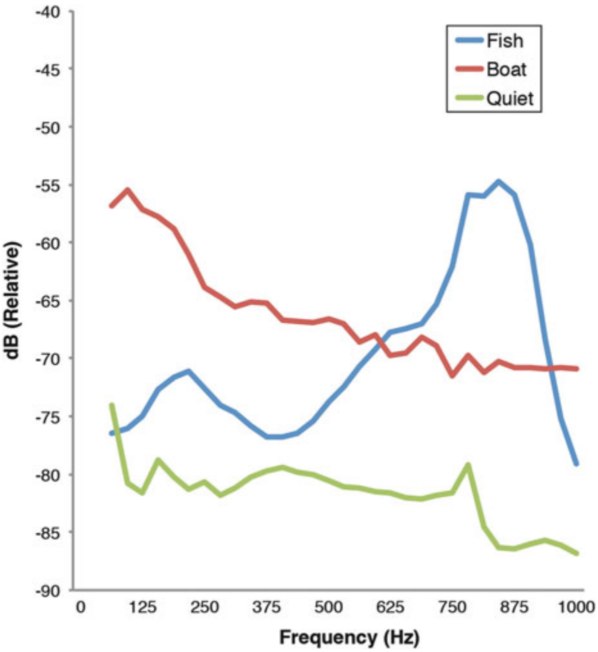
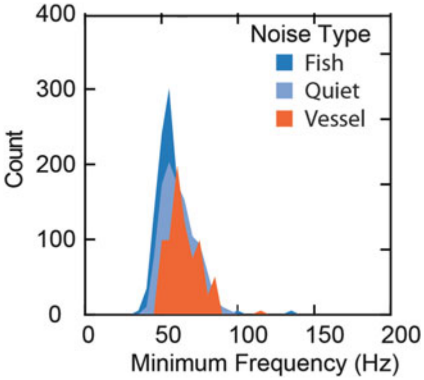


Fig. 99.1 Relative spectral density of the three noise conditions (quiet, boat noise, and fish chorus sounds) showing the relative energy distribution between 30 and 1,000 Hz

Fig. 99.2 Distribution of minimum frequency from right whale upcalls measured in each of the three noise conditions



For this analysis, we focused on a particular call type, the right whale upcall (Clark 1982), with a signal-to-noise ratio >10 dB. A comparison of the background noise levels and call parameters showed variations in right whale calling behavior that were correlated with the frequency distribution of the background noise (Fig. 99.2). Significant variation was found for the minimum frequency (f_{min}), peak frequency (f_{peak}), and duration (Dur) of upcalls in the three noise conditions [f_{min}: $F(3,1051)=18.1$, $P<0.001$; f_{peak}: $F(3,1051)=4.8$, $P<0.001$; Dur: $F(3,1051)=16.6$, $P<0.001$].

4 Discussion

The frequency distribution and intensity of background noise levels varied significantly among periods of increased biological noise (from fish chorus) and increased anthropogenic noise (from boats) when compared with baseline conditions. The distribution of right whale upcall parameters also varied in different background noise conditions, consistent with short-term behavioral plasticity in response to the shifts in background noise. When the dominant background noise was lower in frequency than the whale calls, the minimum frequency shifted higher. When the dominant background noise was higher in frequency than the whale calls, the minimum frequency shifted lower. These results have implications for the description of the acoustic behavior of any sound-producing organisms, indicating that behavioral plasticity in varying background noise may introduce increased variation to stereotyped signals. It is likely that changes in the background noise conditions may impact the frequency and duration characteristics of signals produced by other species and should be taken into account when studying and quantifying parameters of signals.

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Chapter 100
Renewables, Shipping, and Protected Species: A Vanishing Opportunity for Effective Marine Spatial Planning?

Loren M. Petruny, Andrew J. Wright, and Courtney E. Smith

Abstract Anthropogenic noise is a by-product from human activity that impacts protected species and is increasingly being considered in environmental management decisions. Offshore energy development presents a navigational hazard to existing shipping, making the locations of these two sources of noise mutually exclusive. This fact means that licensing decisions are stepping into the realm of coastal and marine spatial planning (CMSP). To be effective, conservation measures must also be considered in the CMSP process to mitigate potential cumulative adverse effects associated with resource development, particularly with multiuse conflicts. Thus managers should consider shipping lane relocation to make environmentally optimal decisions.

Keywords Spatial planning • Marine renewables • Shipping • Noise impacts • Cumulative effects

1 Introduction

Competition for space within coastal and marine environments for recreational use, industrial development, and commercial shipping inevitably leads to the introduction of underwater noise, which usually has potential adverse effects on marine life. Whereas the short-term impacts of high-intensity impulsive sounds (such as those generated from active sonars, seismic air guns, and impact pile drivers) have been the subject of much recent study and debate, attention has recently shifted to efforts

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to provide a better understanding of the long-term consequences of continuous exposure to increasing ambient noise levels (Southall et al. 2007, 2009; Clark et al. 2009; Rolland et al. 2012). Low-frequency ambient-noise levels throughout much of the northern hemisphere have increased at an average rate of 3 dB/decade over the last 50 year (Andrew et al. 2002; McDonald et al. 2006). This increase is largely a result of increased commercial shipping. The wide breadth of vessel designs, propulsion systems, and operating speeds create a variety of acoustic outputs but that output dominates lower frequency ranges and commonly propagates over great distances. As a point of reference, it is estimated that noise emitted from medium-sized ships have source levels ranging from 130 to 160 dB re 1 μPa at 1 m, with a frequency range of 20–10 kHz (Richardson et al. 1995). Specific groups of marine species that are most sensitive to these ranges of acoustic output are most likely to be affected by noise.

In the United States, the US Endangered Species Act (1973, as amended through 2004) as well as the US Marine Mammal Protection Act (1972, as amended through 2007) drives the majority of management criteria for these species with respect to noise. Current noise exposure thresholds for assessing the onset of potential noise impacts on marine mammals were developed by and are regulated by the US National Oceanic and Atmospheric Administration (NOAA) Fisheries Service. The threshold associated with noninjurious "harassment" of cetaceans by exposure to impulsive sounds is 160 dB re 1 μPa at 1 m but is reduced to 120 dB re 1 μPa at 1 m for continuous noise sources. Pinnipeds (i.e., seals and sea lions) have a less sensitive hearing range, with subsequent harassment thresholds of 180 dB re 1 μPa at 1 m for impulsive sounds and 160 dB re 1 μPa at 1 m for continuous sounds (NOAA Fisheries 2013).

In the case of cetaceans (i.e., whales and dolphins), presently growing ambient noise continues to encroach on their communicative space, thus limiting hearing capabilities by masking the acoustic signals essential for social exchanges, predator avoidance, and foraging activities (Clark et al. 2009). This is of particular concern for protected species. For example, passive acoustic monitoring within the Stellwagen Bank National Marine Sanctuary showed extensive overlap of ship noise and phonations of North Atlantic right whales (*Eubalaena glacialis*), which effectively reduced their communicative space by 67% (Clark et al. 2009; Hatch et al. 2012). The chronic exposure of marine life to anthropogenic noise is cause for concern because it may commonly combine with other factors leading to chronic stress in a species (Wright et al. 2007a, b; Wright 2009; Rolland et al. 2012).

Renewable energy development will soon add to the growing list of anthropogenic noise sources because multiple offshore wind projects are in various stages of planning and development throughout United States' waters but especially in the North and mid-Atlantic. Noises associated with these projects are derived from a number of sources, which vary widely depending on the development stage of the project. For example, there will be increased vessel traffic associated with both siting and construction surveys and site characterization surveys, both of which will involve seismic surveys with impulsive signals associated with "boomers" and "CHIRPS." The construction phase is widely considered to be the greatest source for anthropogenic noise associated with offshore wind development (Thomsen et al. 2006).

Depending on the foundation and structure of the wind turbine generator (WTG), pile driving during construction may be one of the greatest noise sources. For example, some WTGs may have monopiles up to 6 m in diameter, which require high-impact pile driving to secure the turbine's foundation to the seafloor.

In contrast, gravity-based (or jacket) turbine foundations and floating turbine platforms may require little-to-no pile driving and thus generate significantly lower noise levels during construction. Once operational, the noise associated with all wind turbines is considered to be substantially less disruptive to cetaceans in general, although the low frequencies are likely audible to, and thus may affect, some of the baleen whales (Madsen et al. 2006). However, this generalization may not hold depending on the scale and spacing of each specific project. For example, a larger-than-typical number of turbines spaced farther apart could necessitate the constant presence of tender vessels, which are required to maintain WTGs (Madsen et al. 2006).

2 Marine Spatial Planning Regarding Noise

Several nations assert the importance of regulating noise levels within the boundaries of critical habitat for protected species or throughout all waters within their jurisdiction (e.g., EU Marine Strategy Framework Directive as described by Erbe et al. [2012]). However, given the plethora of sound sources and the distances over which sounds can propagate underwater, the potential biological and ecological consequences of cumulative exposures to multiple noise sources can only be effectively managed through incorporation within a larger management framework. For example, emerging planning initiatives within the United States (e.g., Interagency Ocean Policy Task Force 2009) may integrate multiple sources of information to encourage the efficient usage of marine spaces. However, there is a clear disconnect between the biological or ecological impacts of ever-increasing anthropogenic activities and marine spatial planning (Foley et al. 2010).

The emergence of marine renewable energy development offers a promising, but likely fleeting, opportunity to consider the potential adverse impacts of noise while making decisions regarding future coastal (CMSP) and marine spatial planning (MSP). This is so because the majority of the various proposed or planned renewable energy installations will act as navigational hazards to navigational radar and ship movements (Atlantic Coast Port Access Route Study [ACPARS] 2012). The industries of shipping and wind energy development are thus mutually exclusive, bringing about one suggestion of a buffer of at least 5 nm between the shipping lanes and wind turbine generators (WTGs; ACPARS 2012). No matter the exact distance of exclusion, the long-term existence of marine renewable sites will have the effect of restricting ship traffic. Given that the vast majority of potential noise impacts from WTGs (with respect to protected marine species such as marine mammals) are expected mainly during the wind farm construction phase but then the area is relatively quiet for the long term, it could be argued that there should be consideration for placement of renewable projects in locations that are known to be important to marine wildlife. After the brief construction phase, the presence of the marine wind farm infrastructure may reduce cumulative impacts associated with exposure to multiple stressors like sound and ship traffic (International Whaling Commission Scientific Committee 2012).

Once the locations of fully operational renewable installations have been set, options for moving shipping lanes for the benefit of marine species will become much more limited. Accordingly, it is appropriate to consider future renewable installations and shipping activity together, which will require a more holistic CMSP strategy that has typically been implemented to date. To achieve this, demonstration and early-stage projects should be used to address operational impacts on baleen whales that have not been assessed with any great detail at existing European wind farms (see Madsen et al. 2006). Similarly, additional efforts should be made during these early projects to acquire more information about coastal baleen whales most likely to be affected by both industries to inform the management process. Only then can these industries be located with due consideration of their long-term impacts through a comprehensive CMSP framework. This concept may be of particular use along the Atlantic Coast where competition for access to marine resources between shipping and offshore wind development is particularly great.

At the present time, a number of offshore wind installations are planned for the state and federal waters of the North and mid-Atlantic, with the first commercial lease issued for the Cape Wind project off Nantucket, MA (Bureau of Ocean Energy Management 2013). The installation of the offshore WTGs planned for this coastal region have been instrumental in shaping and implementing regulations to mitigate noise from construction of offshore facilities. For example, a recent partnership between nongovernmental organizations and deepwater wind developers led to a well-timed mitigation plan for construction (i.e., pile driving) on the planned Block Island wind farm during a time when North Atlantic right whales are not expected in the area (Salit 2013). However, consideration of the knock-on environmental consequences of limiting shipping does not yet appear to have been considered. Although efforts are currently underway to establish voluntary noise reduction guidelines within the International Maritime Organization (IMO), this is unlikely to reduce ship noise greatly in the near future. Beyond the voluntary nature of these guidelines, the majority of potential ship modifications aimed at reducing noise contributions can only be economically incorporated into newly built ships, meaning that widespread implementation of such practices will take decades (Hatch et al. 2008, 2009). Thus, it is important and appropriate to incorporate ship noise into decisions relating to lane locations for the foreseeable future.

3 Conclusions

Given the connections between the acoustic outputs associated with renewable energy development and commercial shipping, it seems clear that a CMSP approach is merited, consistent with the current position regarding CMSP in the United States.

However, implementing this kind of spatial planning would require rapid and transparent information sharing to identify and address the notable information gaps as the offshore renewable energy development process moves forward. This would, in turn, require a high level of coordination in MSP and thus cooperation between the private and public stakeholders involved as well as academic institutions. Several of these systems are already being developed in the United States, such as the formation of an interagency underwater sound field working group and development of national data systems (e.g., see ocean.data.gov, the NOAA CMSP Data Registry, and MarineCadastre.gov; Wright 2009). If regulatory efforts were directed with the end goal of merging commercial and conservation efforts in this way, marine spatial planning should be able to identify environmentally preferred solutions to the combined noise from shipping and renewable energy projects while allowing offshore renewable development with associated safety benefits to shipping. From a wider public policy perspective, this effort could itself become a model for the protection.

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Chapter 101
Are the 1/3-Octave Band 63- and 125-Hz Noise Levels Predictive of Vessel Activity? The Case in the Cres–Lošinj Archipelago (Northern Adriatic Sea, Croatia)

Marta Picciulin, Linda Sebastianutto, Caterina Maria Fortuna, Peter Mackelworth, Draško Holcer, and Nikolina Rako Gospić

Abstract A 3-years sea ambient-noise (SAN) monitoring was carried out in the Cres–Lošinj Archipelago (Croatia), where a bottlenose dolphin population is threatened by unregulated nautical tourism. A total of 540 5-min SAN samples were collected and analyzed in an Indicator 11.2.1 (Marine Strategy Framework Directive) perspective. The 1/3-octave band center frequencies of 63 and 125 Hz (re 1 μPa·rms) proved to be predictive of local predominant ship type over time. However, the noisiest band level was centered on 200 Hz. We therefore suggest measuring a wider frequency band than those requested in Indicator 11.2.1.

Keywords Noise • Boat • Dolphins

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1 Introduction

Several studies have shown that ambient-noise levels constantly increased over the last decades (Andrew et al. 2002; Ross 2005; Slabbekoorn et al. 2010). Sea background noise comes from a variety of sound sources of both natural (physical and biological) and anthropogenic origin (Richardson et al. 1995; Hildebrand 2009). Anthropogenic sounds may be of short duration (e.g., impulsive such as from seismic surveys and piling for wind farms and platforms as well as explosions) or be long lasting (e.g., continuous such as dredging, shipping, and energy installations), affecting organisms in different ways ranging from nil to severe (Tyack 2008; Slabbekoorn et al. 2010; van der Sluijs et al. 2011). As a result, underwater noise became an important aspect of the Marine Strategy Framework Directive (MSFD) adopted by the European Union in July 2008 (European Commission 2008), which aims to achieve a good environmental status (GES) of the European marine environment by 2020. The MSFD considered both the distribution in time and place of loud-, low-, and midfrequency impulsive sounds (Criterion 11.1.1) and the trends in time of continuous low-frequency sound (Criterion 11.2.1). Here we are interested in Indicator 11.2.1 that requests monitoring of the trend in the ambient-noise level within the 1/3-octave bands of 63 and 125 Hz (center frequency; re 1 μPa root-mean-square [rms]; average noise level in these octave bands over 1 year) measured at observation stations. The choice of these octave bands is based on the scientifically justifiable signatures of anthropogenic noise that avoid most naturally generated sources. The MSFD indicators could help in evaluating the quality of the marine environment affected by the intense boat traffic, especially in the coastal areas where boat noise represents one of the most dominant underwater anthropogenic noise sources. The aims of the present paper are (1) to describe the results of a 3-years sea ambient-noise monitoring (2007–2009) in the Cres-Lošinj Archipelago, where local cetacean and fish communities are threatened by unregulated nautical tourism and coastal construction (Rako et al. 2012), by using the 63- and 125-Hz 1/3-octave bands and (2) to verify if these bands levels are predictive of local boat traffic in these coastal waters.

2 Materials and Methods

The study area of ~545 km^2 is located in the Kvarnerić region (Northeastern Adriatic Sea, Croatia). It includes steep rocky shores and a seabed patched with muddy areas and sea grass flats. Sea depth is on average 70 m (Arko-Pijevac et al. 2003). The sea currents rarely exceed an average speed of 0.5 kn, while the sea temperature ranges between 7 and 15 °C in the winter and 22 and 25 °C in the summer (Favro and Saganić 2007).

From 2007 to 2009, the acoustic surveys were carried out monthly at ten predefined acoustic stations grouped in three areas characterized by different proximities to major tourist and municipal locations on land (high-, medium-, and low-anthropogenic impact areas; for details on recording methods, see Rako et al. 2012).

A total of 540 5-min sea ambient-noise (SAN) samples (frequency range: 25–40,000 Hz) were collected: 300 were made during the "tourist season" (TS; June to September; 30 ± 3 [mean ± SD] per acoustic station) and 240 samples were made in the "nontourist season" (NTS; October to May; 24 ± 2 per acoustic station). Data were analyzed for the 1/3-octave band standard center frequencies in terms of instantaneous sound pressure level (SPL; L-weighted; 63–20 kHz rms fast) by using SPECTRA RTA software calibrated with a signal of 100 mV rms at 1 kHz (sensitivity: −170 dB re 1 µPa). Subsequently, the equivalent continuous SPLs ($\mathrm{SPL}_{\mathrm{Leq}}$) for vessels and SAN were calculated by averaging the SPLs over 60 s. In an Indicator 11.2.1 perspective of the "continuous low-frequency sound," 1/3-octave bands of 63 and 125 Hz (re 1 µPa·rms) were considered.

During the acoustic sampling, data on vessel presence, type, and distance from the monitoring location were collected visually using FUJINON 7 × 50 marine binoculars. Seven vessel types were defined depending on size, type of movement, and engine power (HP): motor yacht (MY), speed boat (SB), motor boat (MB), sailing boat on engine (SailB), trawler (TW), gillnetter (GN), and tour boat (TB), according to Rako et al. (2012).

For statistical analysis, when the assumptions for normality and homogeneity of variances were met, data were analyzed with ANOVA, whereas when assumptions were not met, data were analyzed using nonparametric tests: Mann–Whitney *U*-test (for two groups) and Kruskal-Wallis test (for more than two groups), with an α level of 0.05. A Spearman rank correlation test was used to correlate the 63- and 125-Hz noise levels with the boat presence.

3 Results

3.1 1/3-Octave Band Levels

Figure 101.1 shows the average 1/3-octave band levels recorded during the monitoring period. It is possible to notice that the highest average decibel value (re 1 V/µPa) refers to the 200-Hz band (123.9 ± 6 [SD] dB re 1 µPa; min = 96 dB and max = 142 dB). The average levels for the 63- and 125-Hz bands recorded in the area during the monitoring period were 115.3 ± 7 (SD) dB re 1 µPa (min = 96 dB and max = 142 dB) and 116.3 ± 6.6 dB re 1 µPa (min = 92 dB and max = 136 dB), respectively (Table 101.1).

3.2 Temporal and Spatial Variability of 1/3-Octave Bands of 63 and 125 Hz

A significant year-to-year decrease was found during the monitoring period for both band levels [ANOVA; $F(2{,}537) = 7.7$, $P < 0.001$ and $F(2{,}537) = 3.8$, $P = 0.02$, respectively].

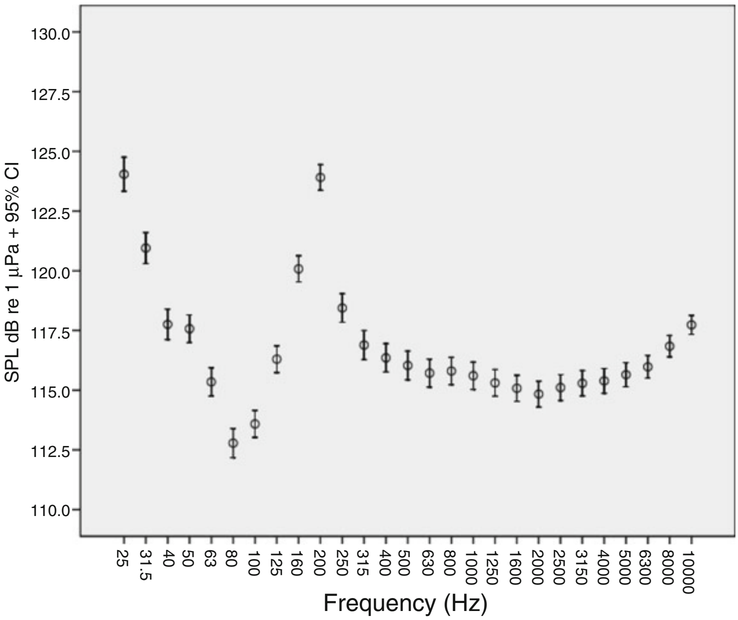

Fig. 101.1 Sound pressure levels (SPLs) of the sea ambient noise recorded in the Cres-Lošinj Archipelago from 2007 to 2009. Values are averages ± SD of the 1/3-octave band; $N = 540$ samples

Table 101.1 Annual values for 63- and 125-Hz centered bands

	63 Hz	125 Hz
Total	115.3 ± 7.0	116.3 ± 6.6
2007	116.7 ± 6.9	116.7 ± 6.2
2008	115.4 ± 6.6	116.9 ± 6.5
2009	113.8 ± 6.2	115.1 ± 7.0

Values are means ± SD in dB re 1 μPa·rms

In the 63-Hz band, noise level was significantly higher during the TS compared with the NTS [two-way ANOVA: $F(1,534) = 11.44$, $P < 0.001$] but did not change between the three impact areas [$F(2,534) = 0.5$, $P = 0.5$]. The interaction found between season and impact area was not significant [impact × season: $F(2,534) = 1.6$, $P = 0.2$]; however, a Bonferroni post hoc test showed that the noise level in the high-impact area was significantly higher during the TS ($P = 0.002$).

The 125-Hz band level varied significantly between seasons [$F(1,534) = 12.7$, $P < 0.001$] and among the three impact areas [two-way ANOVA: $F(2,534) = 3.2$, $P = 0.04$]; the interaction between season and impact area was not significant [interaction impact × season: $F(2,534) = 2.4$, $P = 0.08$]. Again, a significantly higher level of noise was found during the TS only in the high-impact area (Bonferroni post hoc test: $P < 0.001$).

3.3 Boat Spatial and Temporal Distribution

The total number of boats within the study area did not change significantly during the 3-years monitoring period (Kruskal-Wallis test: H [2, $N=540$ samples]$=2.08$, $P=0.35$), but they were significantly more frequent during the TS compared with the NTS (Mann–Whitney U-test: $U=24{,}689$, $P<0.001$). Within the study area, TBs, MYs, SBs, and SailBs were recorded more often during the TS than during the NTS (Mann–Whitney: $P<0.001$ for all; Fig. 101.2), whereas trawlers (TWs) were more frequently spotted during the NTS ($P<0.001$).

Taking into account the three areas of different anthropogenic impact, during the NTS, the number of boats did not change, whereas significant variations were found during the TS (Kruskal-Wallis test: H [2, $N=300$ samples]$=35.76$, $P<0.001$); multiple comparisons showed that the total number of boats observed in the high-impact area was higher than in the medium-impact area ($P=0.004$) and low-impact area ($P<0.001$) and that the number of boats in the medium-impact area was again higher than in the low-impact area ($P=0.008$). Out of all the boat categories, during the TS, only SBs were present in a significantly higher number in the high-impact area compared with the medium-impact and low-impact areas (Kruskal-Wallis test: H [2; $N=540$ samples]$=36.5$, $P=0.003$; multiple comparison high vs. medium, $P=0.003$ and $P=0.002$, respectively). All together, the SB was the most frequent boat type observed during the 3-years monitoring period (Fig. 101.2).

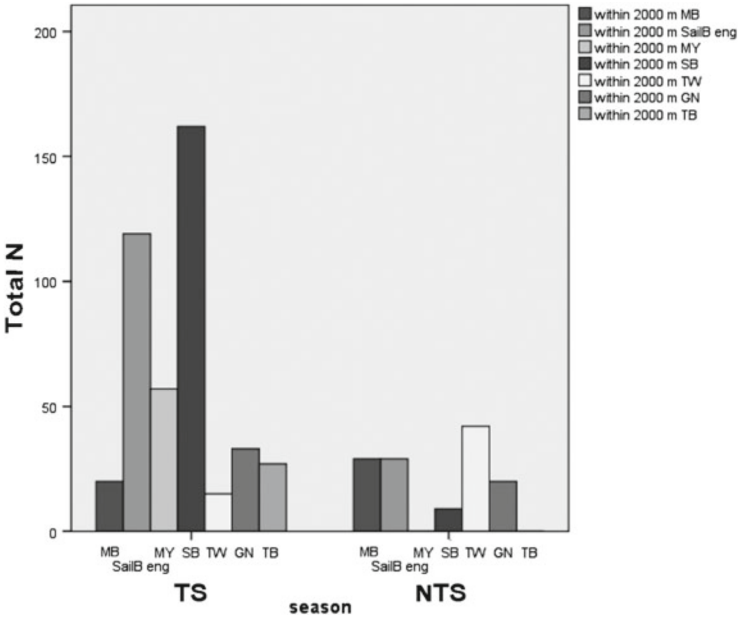

Fig. 101.2 Seasonal intensity of leisure boating during the tourist (TS; June to September) and nontourist (NTS; October to May) seasons. *MB* motor boat, *SailB eng* sailing boat on engine, *MY* motor yacht, *SB* speed boat, *TW* trawler, *GN* gillnetter, *TB* tour boat. *N* number of recorded boats

3.4 Correlation between the 63- and 125-Hz Bands and Boat Presence

We found a positive correlation between the 63- and 125-Hz noise levels and the total number of boats (Spearman rank-order correlation: $P<0.05$, $\rho=0.097$ and $\rho=0.121$, respectively). More precisely, a positive correlation was found between the 63-Hz band level and TB and SB presence (Spearman rank-order correlation: $P<0.05$, $\rho=0.107$ and $P<0.05$, $\rho=0.136$, respectively) as well as between the 125-Hz band level and MY, TB, and SB presence (Spearman rank-order correlation: $P<0.05$, $\rho=0.131$; $P<0.05$, $\rho=0.155$; and $P<0.05$, $\rho=0.202$, respectively).

4 Discussion

The Cres-Lošinj Archipelago represents a popular tourist destination in the northern part of the Croatian Adriatic Sea; since the 1960s, tourism has developed and become one of the most dominant economic sectors in this region (Mikačić 1994). Activities related to tourism are particularly intense during the summer, resulting in a rapid increase in the number of motorized vessels frequenting the area (Rako et al. 2012). Nevertheless Cres and Lošinj waters are an important feeding and nursing ground for the locally resident bottlenose dolphin (*Tursiops truncatus*, Montagu, 1821) population (Bearzi et al. 1997; Fortuna 2006). A recent study (Rako et al. 2013) demonstrated that the noise related to the intense leisure boating causes significant seasonal displacements of resident bottlenose dolphins within this marine habitat. Using the 63- and 125-Hz 1/3-octave bands for monitoring boat presence is therefore of particular interest.

Our results highlighted a positive correlation between the 63- and 125-Hz band noise levels and the number of boats observed in the study area (irrespective of boat type). This explains the season-dependent increment in noise levels across both 1/3-octave bands (63 and 125 Hz) found during the TS, which is characterized by the increased number of boats present.

More precisely, the most frequent type of boat observed during this study in the archipelago was the SB; its presence was particularly high at the stations located close to the important urban and tourist centers (high-impact area) than in the others. Because we found a positive correlation between TB and SB number and 63- and 125-Hz band levels and that the recorded noise in these bands was significantly higher in the high-impact area than in the others during summer, we conclude that the 63- and 125-Hz band levels are predictive not only of the total boat traffic, in agreement with the assumption of the MSDF, but also of the most frequent boat type in the area.

It has to be noted that MYs together with SBs represent the primary source of anthropogenic noise in the archipelago, with particular reference to the high-impact area (Rako et al. 2012). In addition, both SB and MY noise peak at 125 Hz (Rako et al. 2012). If this can explain the correlation between MY number and the 125-Hz band, a nonsignificant correlation between MYs and 63 Hz could likely be related to a much smaller number of MYs in comparison to the number of SBs in the area.

Regarding the monitoring trend, it still remains unclear why the 63- and 125-Hz band levels decreased during the period of 2007–2009, although a relatively stable number of boats (total boats as well single boat types) were observed in the archipelago.

Last but not least, it has to be stressed that the noisiest band level recorded in the Cres-Lošinj Archipelago was not centered either on 63 Hz or on 125 Hz but on 200 Hz; this is in agreement with other studies carried in shallow water, such as the Baltic Sea, where ambient noise peaks at higher levels than these two frequency bands (as reported in van der Graaf et al. 2012). When exploring the use of these bands, not only for evaluating trends but also for defining a good environmental status (and therefore, indirectly, for evaluating the local impact of noise on marine fauna), we suggest the consideration of a wider frequency range than that in Indicator 11.2.1. This conclusion supports a similar recommendation expressed by the MSFD Technical Subgroup on Underwater Noise to the European Commission that provided guidance on implementing aspects of the MSFD under Descriptor 11 (van der Graaf et al. 2012).

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Chapter 102
The Good, The Bad, and The Distant: Soundscape Cues for Larval Fish

Julius J.B. Piercy, David J. Smith, Edward A. Codling, Adam J. Hill, and Stephen D. Simpson

Abstract Coral reef noise is an important navigation cue for settling reef fish larvae and can thus potentially affect reef population dynamics. Recent evidence has shown that fish are able to discriminate between the soundscapes of different types of habitat (e.g., mangrove and reef). In this study, we investigated whether discernible acoustic differences were present between sites within the same coral reef system. Differences in sound intensity and transient content were found between sites, but site-dependent temporal variation was also present. We discuss the implications of these findings for settling fish larvae.

Keywords Underwater soundscape • Coral reef • Larval recruitment • Demersal fish • Biophony

1 Introduction

Sounds are produced by the numerous organisms present on a reef, from sonic booms created by snapping shrimp to a plethora of different fish vocalizations that combine to create a noisy soundscape (Au and Banks 1998; Popper et al. 2003). The sound generated by a reef propagates for kilometers into the ocean due to the high transmission of sound in water and is loud enough to be detected by hydrophones up to 15 km away (McCauley and Cato 2000). The soundscape provides a crucial cue for the

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recruitment of fish and crustacean larvae returning to reefs after a development stage spent in the open ocean (reviewed in Montgomery et al. 2006). Larvae can use sound to orient toward reefs and can potentially use multiple types of acoustic information to discriminate between reefs and gauge the likely distance from them (Simpson et al. 2005; Radford et al. 2007). The larval stage is the main dispersal stage for the majority of reef organisms and the larval supply directly affects population dynamics on the reef (Berumen et al. 2012). The effect that sound may have in influencing larval recruitment has been investigated through simulation models (Armsworth 2000; Codling et al. 2004, 2007; Staaterman et al. 2012). However, without information on natural variation in the sound of reefs coupled with studies of the responses of fish to reef noise in complex acoustic environments, these models cannot yet be utilized to predict recruitment patterns. The response of larvae is of particular interest because sound may provide more information about reefs than their simple presence. Information relayed within the soundscape could provide larvae with valuable knowledge on reef structure and community, potentially influencing larval orientation toward particular types of reef sound to maximize fitness. One study so far has revealed a link between sound levels and biological indicators of reef health including hard coral cover and fish abundance (Kennedy et al. 2010). Soundscapes have been found to differ between types of coastal habitat (Radford et al. 2010) and between geographical regions (Staaterman et al. 2013). Preliminary work has further revealed that reefs across a gradient of different quality possess distinct sound characteristics (Piercy et al. 2014). The question of whether discernible acoustic differences exist between sites within the same coral reef system, potentially providing larvae with localized microhabitat information as they approach potential settlement sites, remains unresolved.

In this study, we investigated reef sound within a single reef system in the Wakatobi National Park, Indonesia, located centrally in the Coral Triangle, which hosts the greatest marine biodiversity. We characterized sound over a relatively small area (<4 km^2) using (1) the root-mean-square (rms) sound intensity (determined by the density of sound-producing organisms on the reef, the distance from the reef, and characteristics of the bathymetry surrounding the reef) and (2) the transient content, a measure of the number of brief (<10-ms) high-intensity acoustic events typical of snapping shrimp. These measures were adopted as two of the simplest forms of information available to orienting larvae. With this approach, we explore the potential value of soundscapes for larvae selecting a habitat over small spatial scales.

2 Materials and Methods

2.1 Sites

The fringing reefs in Hoga, Wakatobi National Park, South Sulawesi, Indonesia, are surrounded by waters >100 m deep. These reefs are situated in the center of the Coral Triangle and are among the most species rich in the world (Veron 1995). Site recordings at seven sites along the continuous reef in Hoga were used to examine

Table 102.1 Geographical locations of sites in Hoga, Indonesia, including marine protected area status and description of sites used for recording sound for between-site comparisons and diurnal variation

Site	Geographical reference	Site description	Study type
Pak Kasim	5°27′9.8846″ S	Fair HCC, fair SCC, fair fish abundance	BS
	123°45′17.7546″ E	No active management	
Front Beach	5°28′20.2578″ S	Fair HCC, low SCC, fair fish abundance	BS and DV
	123°45′25.326″ E	2001–2007 No-take zone (McMellor and Smith 2010)	
		2008–2012 No active management	
Kaledupa Double Spur	5°28′5.8002″ S	Poor HCC, fair SCC, high fish abundance	BS
	123°42′56.3508″ E	No active management	
Sampela	5°29′3.0114″ S	Low HCC, low SCC, low fish abundance	BS and DV
	123°45′11.073″ E	No active management	
Ridge 1	5°26′46.9062″ S	High HCC, low SCC, high fish abundance	BS
	123°45′19.9038″ E	No active management	
Inner Pinnacle	5°27′9.5148″ S	Information on site not available	BS
	123°44′47.3064″ E	No active management	
Coral Gardens	5°27′22.1256″ S	Information on site not available	BS
	123°45′27.9396″ E	No active management	

HCC hard coral cover, *SCC* soft coral cover, *BS* between site, *DV* diurnal variation

within-reef sound variation, although it is not yet possible to relate these recordings to indicators of quality because characterization of these sites is still in progress. Further details on the location and site description are provided in Table 102.2.

2.2 Sound Recordings

Recordings were made in March 2012 around Hoga Island, Wakatobi National Park, Sulawesi, Indonesia, using a calibrated omnidirectional hydrophone (HiTech HTI-96-MIN with an inbuilt preamplifier, a flat response between 200 and 3,000 Hz, and a <1.5-dB drop between 3 and 22 kHz; High Tech, Inc., Gulfport, MS) and a Sony PCM-M10 audio recorder (16 bit, 44.1-kHz sampling rate; Sony Electronics, Inc., San Diego, CA). The recording levels used were calibrated using pure sine wave signals produced by a function generator (TTi RS components 216-069, TG230, 2 MHz sweep/function generator) and measured in line with an oscilloscope. Three 1-min recordings with 1-min intervals between them were taken 20 m from the reef for each of the seven sites between 1,100 and 1,520 when no significant changes in the active reef community were known to occur. Three 1-min recordings were also taken for Front Beach (FB) and Sampela (SMP) for which the temporal variation at four times during the day (0,700, 1,100, 1,800, and 0,000) over five different days was compared. Recordings were taken only in calm sea conditions (no wave break, force 0–2 on the Beaufort Scale) and clear weather to control for background noise.

2.3 *Acoustic Analyses*

Intensity and Frequency Spectrum

All recordings were divided into 10-s subsamples, and samples with obvious anthropogenic noise (passing boats, waves slapping on hull of the boat) were removed from the analyses. The remaining 10-s recordings were high-pass (100-Hz) and low-pass (5-kHz) filtered using MATLAB (v. R2010a, The MathWorks, Inc., Natick, MA) to focus the analysis on the hearing ranges of coral reef fish (e.g., Wright et al. 2010, 2011) and remove possible electrical noise at low frequencies. The rms sound intensity of each recording was calculated in MATLAB and calibrated according to the full dynamic range determined in the initial calibration (see Section 2.2). Calibrated frequency spectra were obtained using a Blackman-Harris fast Fourier transform (FFT) using windows consisting of 512 samples.

Transient Content

Transient content was calculated using a custom-designed algorithm in MATLAB that divided the 10-s-long recording subsamples into time windows, each one transposed from the previous by a fraction of the window length, and the spectral energy was compared between sequential windows. The level of transient content was dependent on the length of the window analyzed, the overlap between frames, and the threshold value. A window length of 10 ms was adopted to reflect the possible minimum gap detection time between signals in fish (McKibben and Bass 2001). This window rarely covered more than a single "snap" of snapping shrimp, which was the dominant transient sound in all reefs and characteristically spaced by >20 ms. A fixed threshold of ten times the median difference in spectral energy between windows across all reef recordings was adopted so that the energy differences between windows exceeding ten times the median window-to-window energy difference were classified as transient events.

3 Results

3.1 *Indonesia Habitat Spectral Analysis*

All sites followed a similar trend, with narrow peaks between 100 and 700 Hz centered on 500 Hz and a lower broad peak between 1 and 5 kHz centered on 4 kHz (Fig. 102.1a). Three sites (Inner Pinnacle [IP], SMP, and Pak Kasim [PK]) contained a number of narrow peaks within the broad high-frequency peak. These peaks, each separated by ~300 Hz from the next, are possibly generated from harmonic sounds of a previously unidentified organism. No obvious fish vocalizations were audible at those frequencies in the recordings, suggesting that these high-frequency intensity peaks might be produced by invertebrates.

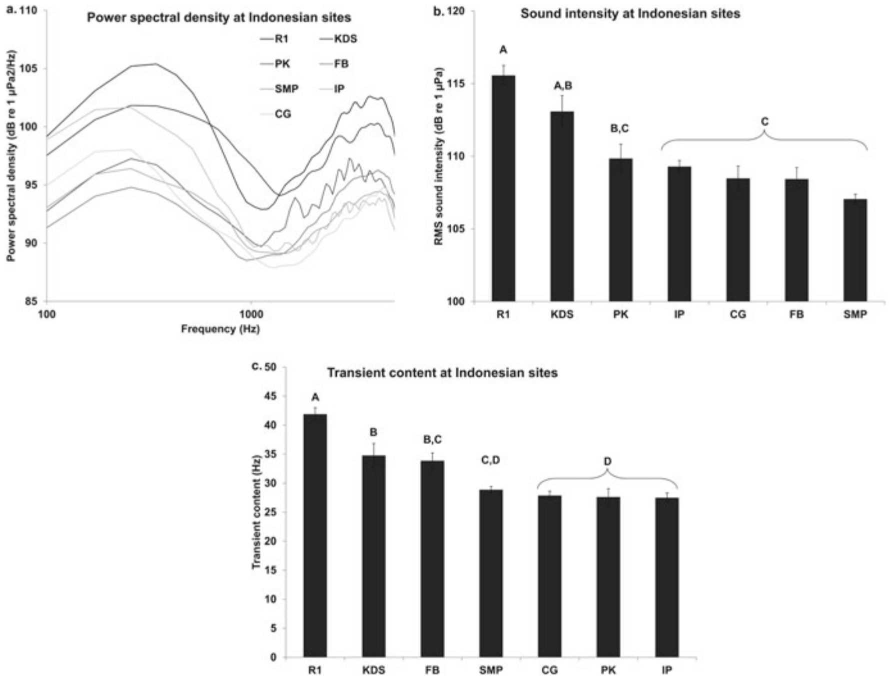

Fig. 102.1 Sound characterization for seven sites around Hoga Island, Wakatobi National Park, Indonesia, from 5 randomly selected 10-s subsamples of three 1-min recordings spaced 1 min apart. (**a**) Power spectral density using a Blackman-Harris fast Fourier transform (FFT) of 512 samples. Frequency peaks <1,000 Hz indicate high levels of fish vocalizations at the reef while the broad peaks >1,000 Hz are indicative of invertebrate noise, produced mainly by the abundant high-energy "snaps" from snapping shrimp. (**b**) Mean ± SD root-mean-square (rms) sound intensity between 0.1 and 5 kHz. (**c**) Mean ± SE transient content. *A*, *B*, *C*, and *D* denote ranks of reefs by broadband rms sound level and transient content. Sites that share the same letter are not significantly different

3.2 Indonesia Site Sound Intensity

The average rms sound intensity obtained from five randomly selected 10-s subsamples between sites in Indonesia was significantly different (one-way ANOVA: $F = 14.84$, $P < 0.001$; Fig.102.1b). Ridge 1 (R1) had a significantly higher mean sound intensity (115.6 ± 0.7 dB re 1 µPa) than all other sites except Kaledupa Double Spur (KDS; 113.1 ± 1.1 dB re 1 µPa; $P < 0.05$, Tukey's post hoc test). KDS, in turn, had a significantly higher sound intensity than all remaining sites except PK (109.9 ± 1.0 dB re 1 µPa; $P < 0.05$, Tukey's post hoc test). There was no significant difference in mean sound intensity between the remaining sites (IP: 109.3 ± 0.4 dB re 1 µPa; Coral Gardens [CG]: 108.5 ± 0.9 dB re 1 µPa; FB: 108.4 ± 0.8 dB re 1 µPa; SMP: 107.1 ± 0.3 dB re 1 µPa; Fig. 102.1b).

3.3 Indonesia Site Transient Content

The mean transient content was significantly different between sites in Indonesia (one-way ANOVA: $F = 18.7$, $P < 0.001$; Fig. 102.1c). R1 had significantly more transient content than all other sites (mean = 43.3 ± 1.1 Hz; $P < 0.05$, Tukey's post hoc test), whereas no significant difference was observed between SMP (mean = 28.9 ± 0.6 Hz), CG (mean = 27.9 ± 0.8 Hz), PK (mean = 27.6 ± 1.4 Hz), or IP (mean = 27.5 ± 0.8 Hz). KDS also had significantly more transient content than all other sites (mean = 34.8 ± 2.1 Hz; $P < 0.05$, Tukey's post hoc test) except RG and FB. FB, in turn, had a significantly higher level of transient content than CG, PK, and IP (mean = 33.9 ± 1.3 Hz; $P < 0.05$, Tukey's post hoc test) but not SMP.

3.4 Indonesia Habitat Temporal Variation in Sound Intensity and Transient Content

The rms sound intensity between 0.1 and 5 kHz using 10-s recordings varied significantly with time of day for both FB and SMP (two-way ANOVA: $F = 3.69$, $P < 0.01$; Fig. 102.2a, d). The rms intensity increased significantly during the dusk chorus at 1,800 compared with daytime recordings at 1,100 across the 5 days of the study (Tukey's post hoc test, $P < 0.05$) but were not significantly different across

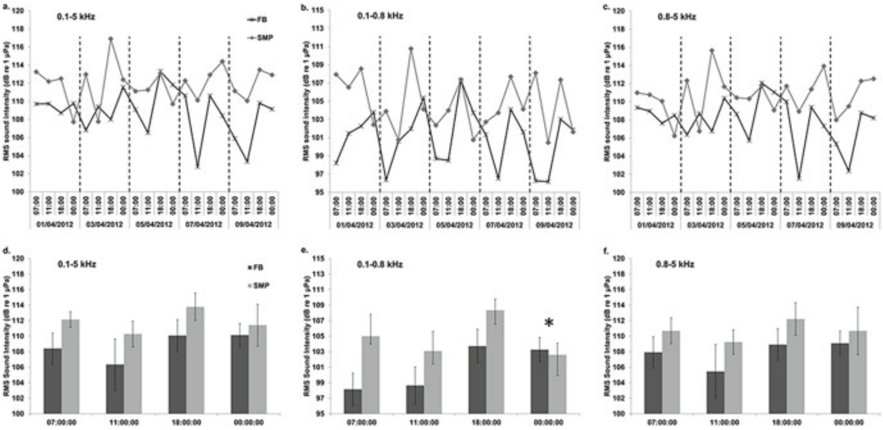

Fig. 102.2 Temporal variation in rms sound intensity in different frequency bins for two sites around Hoga Island, Wakatobi National Park, Indonesia. The rms sound intensity for five randomly selected 10-s subsamples of three 1-min recordings spaced 1 min apart are shown across 5 days for frequencies between 0.1 and 5 kHz (**a**), 0.1 and 0.8 kHz (**b**), and 0.8 and 5 kHz (**c**) at 2 different sites. The mean ± SD rms sound intensity across the 5 days is shown for frequency bins between 0.1 and 5 kHz (**d**), 0.1 and 0.8 kHz (**e**), and 0.8 and 5 kHz (**f**) for the same sites. Sampela (SMP) had a significantly higher sound intensity then Front Beach (FB) for all frequency bins examined. *Asterisk* in (**e**): Time at which the two sites followed a different diurnal pattern

other times of day recorded (0,700, 1,100, and 0,000). There was no significant interaction between site and time of day across this bandwidth. When the sound was decomposed into different third-octave bands, however, a significant interaction between site and time of day emerged for all center frequencies between 400 and 1,000 Hz (two-way ANOVA, 400 Hz: $F=3.93$, $P=0.02$; 500 Hz: $F=7.38$, $P<0.01$; 630 Hz: $F=3.99$, $P=0.02$; 800 Hz: $F=5.59$, $P<0.01$; 1,000 Hz: $F=4.26$, $P=0.02$). In all third-octave bands for which site-dependent temporal variation was observed, except the one centered on 1,000 Hz, the rms sound intensity at SMP followed the same pattern of change as FB between 0,700 and 1,800. However, the rms sound intensity over these frequency bands decreased significantly for SMP between 1,800 and 0,000 (for each center frequency: Tukey's post hoc test, $P<0.001$) but were not significantly different at these two times for FB. For the third-octave band centered around 1,000 Hz, the rms intensity did not change significantly at any time of day for SMP but was significantly higher at 1,800 and 0,000 compared with 0,700 and 1,100 for FB (Tukey's post hoc test, $P<0.001$).

Based on the findings from the analyses of the third-octave bands and visual inspection of the spectrogram, an informed decision was made to group the frequency bands examined under high (800–5,000 Hz) and low (100–800 Hz) frequencies. The rms sound intensities for the low-frequency band were significantly higher at SMP than at FB (two-way ANOVA, $F=31.83$, $P<0.001$), varied significantly with time of day (two-way ANOVA, $F=13.09$, $P<0.001$) and displayed a site-dependent diurnal variation (two-way ANOVA, $F=5.19$, $P<0.01$; Fig. 102.2b, e). The rms sound intensities for the high-frequency band were also significantly higher at SMP than at FB (two-way ANOVA, $F=14.83$, $P=0.001$) and varied significantly with time of day (two-way ANOVA, $F=3.57$, $P=0.03$) but did not display any site-dependent temporal variation (Fig. 102.2c, f).

4 Discussion

This study identified localized differences in the acoustic output of coral reefs coupled with site-dependent temporal variation across some frequency bands. Controlling for daily variation in noise on reefs and abiotic sound sources (e.g., waves and wind; all site comparison recordings made between 1,100 and 1,520 in calm conditions), differences were found in both the sound intensity and transient content for neighboring sites. The relationship of parameters from reef recordings with measures of reef characteristics such as fish abundance and percentage coral cover is currently under analysis. Considering the close correlation found between reef characteristics and acoustic fingerprints in Kennedy et al. (2010) and that differences were also found in the transient content of the sound, which is a measure largely independent of environmental and bathymetric differences, it is possible that specific reef characteristics could be estimated in these recordings.

Temporal variation for the two sites examined in this study supports previous findings (McCauley and Cato 2000) whereby sound intensity was highest during dawn and nighttime (1,800 and 0,000, respectively, in this study) and lower during the daytime. However, this study also found a site-dependent effect in temporal variation for low frequencies (100–800 Hz), suggesting different changes in the community at these sites between daytime and nighttime even over these low spatial scales. This site-dependent effect is possibly caused by differences in fish assemblages as opposed to the invertebrate ones because fish are the dominant sound producers at lower frequencies (Myrberg et al. 1986; McCauley and Cato 2000; Lagardere et al. 2005). It is also worth noting that fish larvae were attracted to the high-frequency component of reef sound in studies by Simpson et al. (2005, 2008). The lack of site-dependent temporal variation for frequencies >800 Hz suggests that this component might be a more reliable indicator of reef presence, which could explain the preference found in settlement stage larvae for higher frequencies in reef noise when orienting toward a reef.

Overall, the meaningful heterogeneity in reef noise coupled with reliable temporal variation for high-frequency sounds may provide recruitment stage larvae with sufficient information to select specific microhabitats in which to settle. This would support previous findings by Radford et al. (2011) in which juvenile fish were capable of responding to sound playbacks from fringing reef and lagoon recordings. A positive correlation between sound intensity and parameters of diversity or abundance even at these small spatial scales would also reinforce the value of reef noise measurement as an assessment tool for reef quality.

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Chapter 103
Terrestrial Soundscapes: Status of Ecological Research in Natural and Human-Dominated Landscapes

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Abstract Soundscape ecological research in terrestrial systems is relatively new. In this paper, I present a brief summary of the origins of this research area, describe research questions related to several research thrusts that are ongoing, summarize several soundscape projects that exist and how these relate to the research thrusts, and briefly describe the work of a global network of scientists, musicians, and engineers that are attempting to move this new field forward.

Keywords Soundscapes • Biophony • Geophony • Anthrophony • Entropy • Acoustic niches

1 Introduction

Soundscape ecology (Pijanowski et al. 2011a, b) is a new area of research that examines how sounds produced by objects over space and time are related to natural and human activities occurring at a place. Three major sources of sound (biological, geophysical, and anthropogenic) are examined simultaneously within coupled natural human landscapes. Soundscape ecology is based on long-term work in bioacoustics, biogeography, psychoacoustics and that of landscape ecology (cf. Turner et al. 2001). Most important, soundscape ecology borrows from the fundamental principle of landscape ecology, i.e., that pattern and process within landscapes are inextricably linked. In other words, soundscapes reflect underlying natural and social processes and patterns in landscapes. As scientists search for ways to study the impacts that humans have on ecosystems, the need for "universal variables," those measures that can reflect both natural and human processes, will become increasingly important. The purpose of this chapter is to summarize the current state of

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soundscape ecological research in terrestrial ecosystems with the hope that parallel efforts in aquatic systems can be developed, or if they are emerging, how they might be harmonized with efforts ongoing in terrestrial systems.

Soundscape ecology has been possible in terrestrial ecosystems because advances in a variety of technologies have enabled researchers to place automated microphones with data loggers in a diverse set of habitats, record near-continuous acoustic information that can be then stored in large storage facilities and analyzed with supercomputers. These acoustic recordings can be analyzed across space and time for patterns that reflect the underlying processes of concern. For example, Pijanowski et al. (2011a) in Tippecanoe County, IN, showed that (1) the diversity of sounds decreases as one proceeds from natural habitats to more human-dominated landscapes and (2) a variety of temporal trends are evident, reflective of the natural histories of the animals that live at a location. Spatial patterns of the landscape lead to certain soundscape patterns; in areas where the habitat is complex or has not been disturbed by humans for a long time, the diversity of the soundscape is high. Temporal patterns, which we call rhythms of nature, are diurnal and seasonal in nature. The dawn chorus (generally an hour before and after sunrise) and dusk chorus (an hour before and after sunset) contain the greatest diversity of sounds because daytime (mostly birds) and nighttime (mostly insects, bats, and amphibians) animals overlap in their vocalizations and/or stridulations. Seasonal patterns are also evident in our midlatitude temperate forest ecosystem; the early spring arrives with a few species of birds and amphibians calling, increasing latter in the spring as more birds arrive at their breeding locations from their tropical overwintering habitats; summer witnesses an even greater acoustic diversity as insects emerge and begin stridulating and birds continue to call, although less so, because their breeding is generally over. In late fall, there is generally a sharp dropoff in biological sounds. The underlying patterns of the natural landscape and geophysical processes (e.g., climate) generate the distinctive biological sounds that occur at a location (Fig. 103.1, green).

Soundscape ecologists are also interested in the sounds produced by the geophysical environment, mostly the sounds created by the movement of fluids, those of air and water (Fig. 103.1, green). Changes in energy can also create sound (e.g., thunder, volcanic eruptions) and these are of interest as well. These geophysical sounds are reflective of the climate regimen of any given area. Thunder and rain produce sounds in patterns that are distinctive; in some areas of the world, they are quite synchronous. For example, in the equatorial regions of the world, within the Intertropical Convergence Zone (ITCZ) in particular, four seasons occur, two dry and two rainy, per year. The length and intensity of these two rainy seasons are studied with considerable detail by climate scientists because these produce the necessary water to grow crops and feed rivers and streams important to aquatic life or to create situations where flooding leads to devastating effects for people on land. Monitoring the geophysical patterns of sounds over many years has the potential to provide important information about how climate may be changing in any given area. Furthermore, many animals have adjusted the frequency or timing of their signals to allow for communication to occur with the natural patterns of geophysical sounds. Changes in climate could alter the ability of some species to communicate

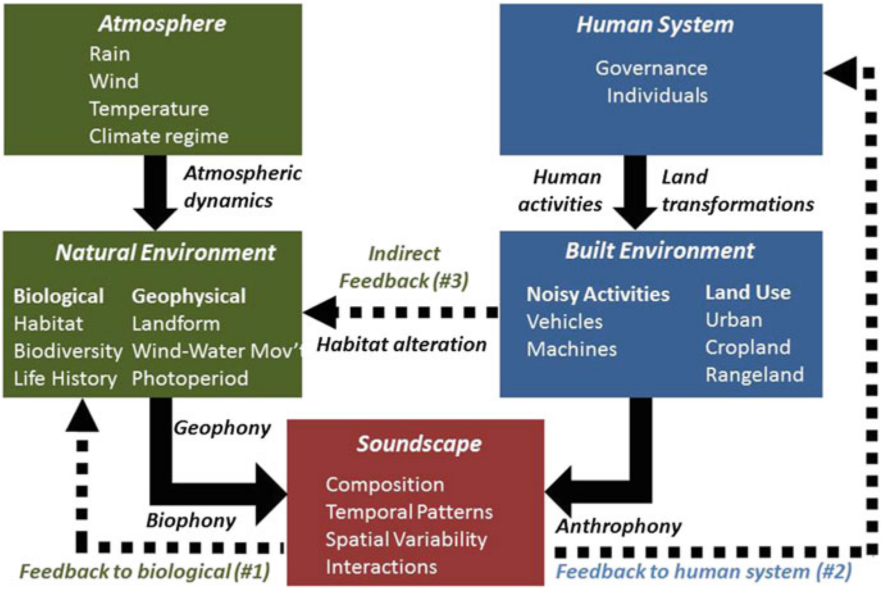

Fig. 103.1 Major components of the soundscape system illustrating the natural and human components of the sources of sounds of a soundscape and the feedbacks that create changes to the soundscape over time

effectively with conspecifics or change the ability of predators to cue into their prey using acoustic signals.

Considerable research has also been conducted on human-produced sounds in terrestrial environments. Urban sounds are created by a variety of human activities and are also governed by policies (Fig. 103.1, blue). Urban soundscape research has progressed significantly in the last 10 years in Europe as efforts to improve the livability of cities has concentrated on reducing noise levels from vehicular traffic and most industrial sources. This effort has led to two important trends: one is to eventually create a set of policies that improves sound quality in cities through efforts known as the ISO/TC 43/SC 1/WG 54 initiative and the second is to work on the human psychological responses of sounds that occur in urban environments. Not all human-produced sounds are considered annoying or classified as "noise" and as such, this work requires careful the consideration of normative responses to sound (Smith and Pijanowski 2014) as well as to the human cognitive reactions to various sounds; for example, the sounds of a church bell provide the people of a community with a sense of place and symbolize to many the nature of the bond between people, but these sounds are only perceived this way in certain areas of the world. This broader area of research that also includes the social science dimension should be more properly labeled as soundscape science because it is not just ecological in nature. Whether "soundscape science" is a more apt term for this more inclusive form of scholarship than "soundscape ecology" will require more time and stronger engagement of the social science community to decide.

One of the most important differences between soundscape ecology research and traditional bioacoustics research is the focus by soundscape ecology on ALL sound sources simultaneously (Fig. 103.1, red). Traditionally, bioacoustics work in terrestrial environments has focused on single-species communication patterns, mostly in isolation with other sounds. Examining all sound sources simultaneously leads to a more community or ecosystem level of focus in soundscape ecology work rather than on a population ecology focus that is characteristic of most bioacoustics work. Separating sound sources is challenging, although not impossible. Given that most biological sounds contain information, their sound patterns are often modulated and more complex than those from wind, water and from human produced objects. Frequencies differ as well; most road noise occurs below 1 kHz; the sounds of amphibians are located in the 2- to 4-kHz range (with interesting exceptions in the tropics); most passerine birds vocalize around 3–6 kHz; and insects call at upper audible frequencies (e.g., cicadas are generally in the 6- to 9-kHz range) or produce regular signals in the 2- to 4-kHz range (e.g., crickets, grasshoppers, katydids). Many bats emit calls (i.e., clicks) in the audible range (around 14–20 kHz) and echolocate objects and prey above human hearing (from 18 kHz to as high as 110 kHz).

Soundscape ecologists have had to develop new terms to describe certain patterns, some of which are borrowed from the music community. The term biophony is used to describe the arrangement in terms of space, time, and spectral features of all biological sources of sound. Here the suffix phony is used to reflect the sound arrangement as one would look at a score of a symphony. A keynote sound is one that is distinguishes an ecosystem; a wolf or loon typifies the northern lake temperate forests of North America, although keynotes are also emitted rarely. A soundscape motif is used to describe a sound heard frequently in the ecosystem; this might be the sound of an ovenbird, a northern warbler, in this same ecosystem.

Currently, there are two general approaches that are being considered in assessing the biological diversity of sounds within ecosystems. The first (Fig. 103.2) in what might be termed species richness measures focuses on using an assessment of all sounds and classifying species using automated computer learning algorithms

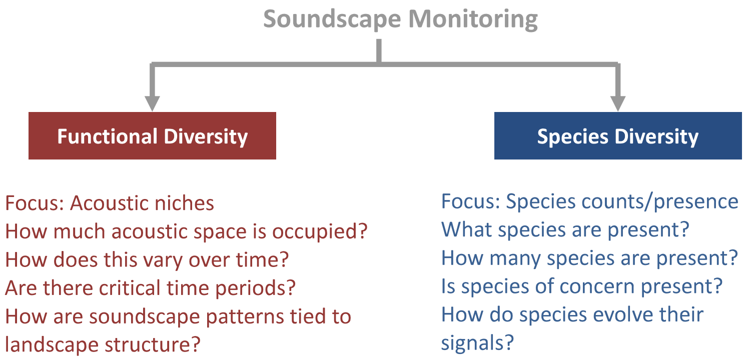

Fig. 103.2 Two main objectives of using soundscape recordings to assess ecosystem health. The first involves the study of species diversity with a focus on the presence/absence of species and species counts at a location. The second examines the role that animal sound signals play within the context of an acoustic niche

that either detect a particular species of interest or sum the total number of vocalizing species at a place or given time. The second, and less well studied, is a more functional approach to quantifying biological sounds. Here, sounds are examined for their niche properties; silence is considered a natural resource that can be filled with a sound. In the tropics, the spectral resources are full, especially during the dawn chorus. We find biological sounds in the subartic and the desert to be far less dense due to reduced species richness and the low abundances of many vocal animals, but the acoustic space in these ecosystems has a considerable source of sound from the geophysical environment, wind especially, so that biophonic–geophonic interactions are likely to be more important in these environments.

It is known that a variety of senses (e.g., sight, sound, smell, touch) help humans create their notion of place. Social scientists (Jørgensen and Stedman 2001; Smith et al. 2011) have referred to this as a sense of place, and soundscape science is now expanding into research that examines how place attachment, place identity, and personally held values are shaped by the natural and human produced sounds of an ecosystem.

2 Broad Research Agenda

My group has focused on six sets of broad research questions that I hope will attempt to lay a solid foundation for this new field over the next decade.

1. Research Thrust 1: Composition Variability. How do soundscapes vary in composition across natural and human disturbance gradients? Are these patterns similar across the planet's different ecosystems? Within certain gradient types (e.g., elevated), do soundscapes vary similarly across the gradient from location to location (i.e., one mountain region to another). Are these patterns consistent with our current knowledge of ecosystem dynamics as reflected in landscape ecology, biogeography, and conservation biology? How are acoustic niches occupied in each ecosystem? How do they vary temporally?
2. Research Thrust 2: Soundscape Metrics. What acoustic composition metrics are sensitive to the space and time variability of the soundscape? Do these metrics reflect biological patterns of animals producing sounds? Can these metrics measure natural and human activities? Can the language and theory of music be used to more rapidly advance the field where complex sounds and the natural orchestration can be studied?
3. Research Thrust 3: Soundscape–Landscape Interactions. How do soundscapes vary with the landscape structural heterogeneity? With climate regimens? With natural disturbances such as fire and pests? Is this knowledge consistent with what we know about how nature responds to these disturbances? How are soundscape dynamics triggered in each ecosystem?
4. Research Thrust 4: Comprehensive Ecosystem Monitoring. Do traditional survey methods correlate with soundscape metrics? How can other automated survey methods be used in parallel with acoustic monitoring? Can acoustics be used in conjunction with large-scale monitoring efforts such as those of the National Ecological Observatory Network (NEON) and the Phenology Network.

5. Research Thrust 5: Soundscapes and People. How do people and animals perceive soundscapes in ways that are relevant to the sustainability of ecosystems and the formulation of noise and natural resource management policies? How does sound create a sense of place for people? How does the sense of place vary culturally and by ecosystem?
6. Research Thrust 6: Global Soundscapes and Citizen Scientists. To gather information on a global scale, efforts are needed to recruit nonscientists to record soundscapes using a variety of instrumentation and/or mobile devices and send these recordings and associated information (e.g., geographic coordinates) to a global recording repository at Purdue University.

3 Ongoing Projects

My group is currently working on the following studies related to the research thrusts above.

1. Long-Term Tippecanoe Soundscape Study. The objective of this study is to continuously record soundscapes in seven locations around the Purdue University campus that span the range from natural habitats with old growth forests to highly human-dominated landscapes of agriculture and urban. We have been recording at these same sites since April 2008 using Wildlife Acoustics SongMeters. Recording protocols include recording in 16-bit WAV stereo using omnidirectional microphones with a 44.1-kHz sampling rate, starting at the top of each hour and recording for 10 min. These settings are referred to as soundscape recording protocol 1. Recorders are set in the early spring and go through early winter. This study is intended to continue for many years, possibly decades, with the objective of using the recordings to monitor how long-term environmental changes, such as those due to climate and land use change, would be affected. Small subsets of these data (see Villanueva-Rivera et al. 2011 for a description of these files and links to downloads) are also being used to test how new processing algorithms and metrics can advance our ability to analyze soundscapes.
2. La Selva Soundscape Study. Two sets of short–term studies have been completed at the La Selva Biological Station in Costa Rica. The first, conducted by Conservation International, attempted to monitor tropical frog distributions across the station. These data were collected in early 2008 in ~22 locations (see Pekin et al. 2012 for more information), several of which were located outside the boundaries of the station farther up Volcan Barva. La Selva Biological Station is an ideal place to examine how soundscape information correlates with tropical vegetation patterns because the National Aeronautics and Space Administration (NASA) and other remote-sensing organizations have designated this site as one of its locations where new sensors (e.g., hyperspectral and light detection and ranging [LIDAR]) are tested and thus many data layers are often available. Because it is one of the most well-studied tropical locations in the world, numerous publications and survey data are available to examine the correlation of

soundscape information with other ecological variables. These recordings were not continuous because only evening (10 min starting at the top of an hour) times (from 1,800 to 2,400 h) were made.

A second set of recordings, made in the fall of 2012, attempted to examine several soundscape gradients at the station and include riverscapes (i.e., how geophony varies from above a river uphill into the riparian zone); vertical (i.e., from the top of the canopy 40 m above the ground to 1 m above the ground); open land to forest core, with a focus on examining the soundscape dynamics of forest edges and comparing them to the forest interiors; and wetland-mesic gradients.

3. Sonoran Desert and Sky Island Soundscape Study. Started in April of 2013, my group placed 32 recorders in the Sonoran Desert located in Tucson, AZ, and then eastward in and near the Chirichihua National Monument (CNM) that is part of the Madrean Sky Island Archipelago. Sky Island harbors some of the greatest biodiversity in North America because up to a dozen life zones (hot-dry desert through to spruce-cedar forests) are located within short distances. Over 300 species of birds and 34 species of bats are located in the CNM. My group is studying how ecosystems recover from fire disturbances by placing sensors in high-impact fire areas and at unburned locations in the same habitat, elevation, and aspect. This long-term study will be one of the first on soundscape ecology to address an important management issue that is not focused entirely on biodiversity.
4. Aldo Leopold Foundation Reserve Project. In 2012, 4 months of continuous recording at 24 sites in the Aldo Leopold Foundation Reserve near Baraboo, WI, were made in an effort to study how soundscape information correlates with bird diversity across the reserve. Over 12 years of bird survey data as part of the Important Bird Area censuses have been made; these data are being examined in conjunction with the soundscape recordings. This work has shown that noise levels are as important as habitat structure in determining the diversity of natural sounds that occur in temperate forests.
5. Wells Reserve Estuarine Study. In collaboration with the Wells National Wildlife Research Reserve, 12 sensors, including hydrophones installed in vernal ponds, have been placed across 6 subhabitats in this fragile coastal zone ecosystem. Long-term recordings will be used to assess how tidal fluctuations control soundscape dynamics.
6. Record the Earth Citizen Science Project. For Earth Day 2014 (April 22, 2014), my group initiated an ambitious project to get people from around the world to download our mobile app for both Apple and Android devices, use the app to record their soundscapes, and answer a few questions about soundscape composition and their emotional response to what they recorded. Users can upload their recordings to a Web-based server where they can “map all of the places where there are soundscapes that make people happy.” On Earth Day 2014, we had recordings from every state, nearly every country in Europe, and about 40% of non-African countries in the world. The site will be maintained for 5 years and is devoted to housing these recordings for users to listen to as well as to promote the preservation of natural soundscapes (www.globalsoundscapes.org).

4 Global Sustainable Soundscape Network

In an effort to bring a diverse set of scholars together to move soundscape ecology forward, a group of ecologists, musicians, and engineers received funding in 2011 from the National Science Foundation's Coupled Natural-Human System Dynamics Program for a Research Coordination Network set of activities. The aim of the grant is to gather these scholars at diverse ecosystems around the world to exchange ideas on how to monitor, analyze, and apply this work to conservation and sustainability efforts. The group calls itself the Global Sustainable Soundscape Network and many of the studies listed above have databases that are shared among network members. Two workshops have been completed, one at the Aldo Leopold Foundation Reserve in Baraboo, WI in the summer of 2012, and the second in Oracle, AZ, in July 2013. Acousticians wishing to join the network can do so at www.soundscapenetwork.org.

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Chapter 104
Effects of Underwater Turbine Noise on Crab Larval Metamorphosis

Matthew K. Pine, Andrew G. Jeffs, and Craig A. Radford

Abstract The development of marine tidal turbines has advanced at a rapid rate over the last decade but with little detailed understanding of the potential noise impacts on invertebrates. Previous research has shown that underwater reef noise plays an important role in mediating metamorphosis in many larval crabs and fishes. New research suggests that underwater estuarine noise may also mediate metamorphosis in estuarine crab larvae and that the noise emitted from underwater tidal and sea-based wind turbines may significantly influence larval metamorphosis in estuarine crabs.

Keywords Crustaceans • Larvae • Settlement • Tidal • Turbine • Underwater sound • Wind • Estuary

1 Introduction

While the global advantages of renewable energy generation are not in doubt, the local environmental impacts must be carefully considered (Inger et al. 2009). Although the underwater noise from operating sea-based wind turbines and the potential impact on marine mammals and fishes are well researched, tidal turbines are still in their infancy, with little detailed understanding of the potential impacts (Inger et al. 2009). The noise from an operating turbine is influenced by several factors, including blade and turbine design, tidal or wind flow velocity, depths, bottom substrate, gearboxes, and weather. The construction and eventual decommission of turbine structures will also be a significant source of underwater anthropogenic noise (Inger et al. 2009; Thomas 2009). The noise from an operating "SeaFlow" tidal turbine has been measured to have a source level of 175 dB re 1 μPa at 1 m,

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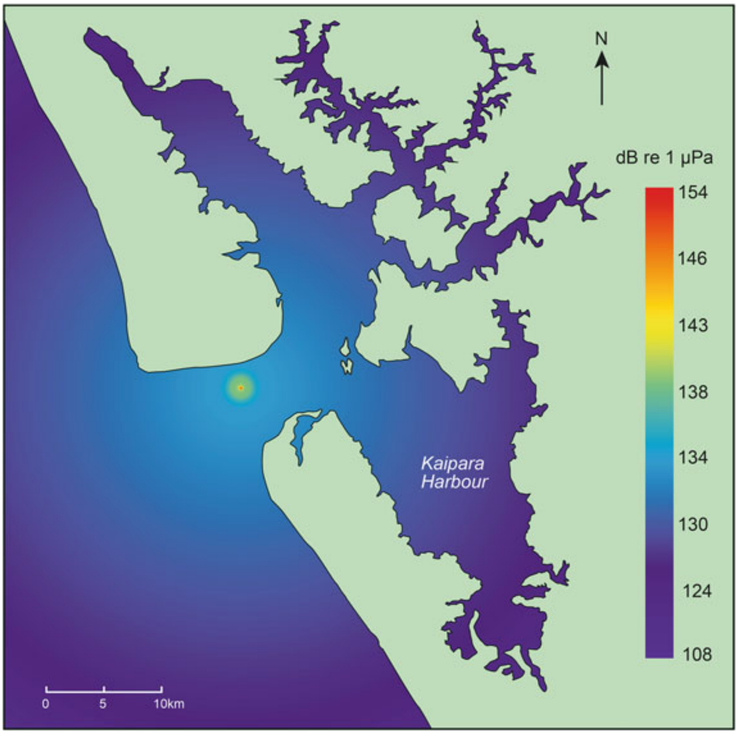

Fig. 104.1 Estimated propagation of underwater wind turbine broadband noise from a point source (source level of 154 dB re 1 µPa at 1 m) in the Kaipara Harbour, New Zealand

with peak pressures at 0.1, 0.8, 2, 5, and 8 kHz (Parvin et al. 2005) at a maximum tidal flow of ~3 m/s (Richards et al. 2007; Lloyd et al. 2011). The noise from an operating sea-based wind turbine has a measured source level of at least 154 dB re 1 µPa at 1 m at an approximate wind speed of 13 m/s, with most energy below 1 kHz (Wahlberg and Westerberg 2005). The noise emitted from operating tidal turbines can travel massive distances and traverse many habitat boundaries. For example, using simple equations from Richardson and Thomson (1995) and Urick (1983), tidal turbine noise can be estimated to travel tens of kilometers before attenuating to ambient noise levels in estuarine habitats (Fig. 104.1).

The larvae of some crustaceans remain within coastal environments while others venture tens of kilometers from the coast before making their way back to the near-shore and metamorphosing from natant larvae (known as a megalopae) into juveniles (Jeffs et al. 2003; Simpson et al. 2005; Mann et al. 2007; Radford et al. 2007; Stanley et al. 2010). To help ensure that larvae settle in a suitable location, they have evolved the ability to detect and orient toward natural underwater noise associated with their preferred benthic habitats (Pawlik 1992; Steinberg et al. 2008; Medina and Tankersley 2010), with a combination of several physical and chemical cues often instigating settlement and metamorphosis once they have reached their preferred settlement habitats (Forward et al. 2001; Gebauer et al. 2004; Steinberg et al. 2008; Stanley et al. 2010). Recent research suggests that natural underwater noise acts as not only an important orientation cue but also a metamorphosis cue in true crabs (Stanley et al. 2010, 2011). Until now, no research had been published whereby the influence of anthropogenic noise on the metamorphosis of crab megalopae was investigated. Here, we discuss new research into the influence of both sea-based wind and underwater tidal turbine noise on the natural metamorphosis behavior in the estuarine crabs, *Austrohelice crassa* and *Hemigrapsus crenulatus*.

2 Turbine Noise Influences the Metamorphosis Behavior in Estuarine Crab Larvae

Within a laboratory setting, the megalopae of *A. crassa* and *H. crenulatus* were exposed to four independent noise treatments that were run concurrently during the experiment. Each individual treatment played back either (1) natural estuarine noise (recorded from a subtidal mudflat); (2) sea-based wind turbine noise; (3) underwater tidal turbine noise, and; (4) a control, whereby the underwater speakers were not switched on. The time to metamorphosis (TTM) for each megalopa in each treatment was recorded and defined as the time taken from the commencement of the experiment to the time until the individual megalopa had settled and metamorphosed into a juvenile crab (Stanley et al. 2010, 2011).

When exposed to natural underwater estuarine noise, the TTM in the megalopae of both *A. crassa* and *H. crenulatus* decreased by 21–31% compared with silent control treatments, 38–47% compared with tidal turbine noise treatments, and 46–60% compared with sea-based wind turbine noise treatments (Fig. 104.2). For experiments consisting of two tidal turbine noise treatments, each treatment being of different source levels, no difference between the TTM in *A. crassa* megalopae were observed, suggesting that spectral composition of the noise is more relevant in explaining the observed behaviors.

3 Potential Ecological Impacts: Future Research

Recent studies pointed out that there is a need to begin to make connections between anthropogenic noise sources and long-term ecological impacts (Slabbekoorn et al. 2010). Research has shown plasticity regarding the TTM in true crabs (Pechenik 1990; Gebauer et al. 1999; Stanley et al. 2010). The duration of the megalopal stage of these crabs can vary depending on the environment within an assumed temporal threshold, after which postmetamorphosis growth and development may be impaired with higher than normal juvenile mortality rates (Pechenik 1990; Weber and Epifanio 1996; Gebauer et al. 1999; Forward et al. 2001; Steinberg et al. 2008). These temporal thresholds are assumed to be represented by the TTM under

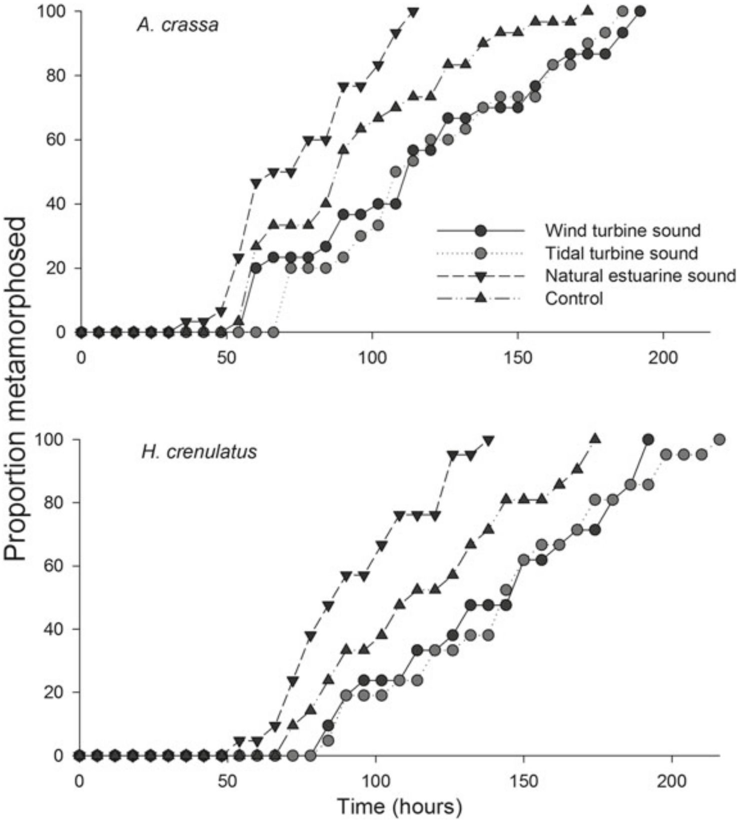

Fig. 104.2 Median time to metamorphosis in two estuarine crab species, *Austrohelice crassa* and *Hemigrapsus crenulatus*, for each sound treatment

conditions where no metamorphosis cues are available (i.e., a silent treatment in sterile seawater). Findings presented in this paper show megalopae metamorphosing beyond such temporal thresholds (as represented by the silent control treatments) when exposed to underwater tidal turbine and sea-based wind turbine noise. Consequently, the long-term recruitment patterns of these ecologically important crabs may be significantly impacted. Further experimentation of the postmetamorphosis behaviors and growth patterns in a range of decapod crab species after chronic exposure to turbine noise is therefore recommended.

Previous research has shown that the larvae of many fish and invertebrates respond to underwater acoustic cues not only for settlement but also for orientation (Simpson et al. 2005; Radford et al. 2007; Vermeij et al. 2010). The findings shown in this paper conclude that underwater turbine noise may impair the physiological development of estuarine crab megalopae by delaying metamorphosis and hypothesizes that other anthropogenic noise sources may elicit similar behavioral responses in crab larvae as well as influence the swimming orientation of megalopae. New research has shown that vessel noise significantly disrupts the orientation behavior in the natant larvae of several fish species, whereby fish larvae actively swim away from a simulated settlement habitat rather than toward it during exposure to vessel noise (Holles et al. 2013). Such behaviors could lead to poorer recruitment of ecologically important fishes, and future research into the potential orientation behavior of crab megalopae in response to anthropogenic noise sources is recommended.

4 Summary

Renewable energy-generating turbines in the sea are becoming increasingly attractive as a shift from fossil fuels is needed to offset further anthropogenically induced climate change (Inger et al. 2009). Therefore, understanding the potential noise impacts these projects may have on the marine environment is crucial for sustainability. Consistent results suggest that underwater turbine noise may significantly alter the recruitment of two ecologically important crab species, therefore potentially changing the benthic ecosystem in areas where turbines are installed. New research, such as that discussed in this paper, extends our understanding of the potential impacts; however, much more conclusive data on long-term ecological impacts are needed.

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Chapter 105
Temporary Threshold Shifts in Naïve and Experienced Belugas: Can Dampening of the Effects of Fatiguing Sounds Be Learned?

Vladimir Popov, Alexander Supin, Dmitry Nechaev, Evgenia Sysueva, and Viatcheslav Rozhnov

Abstract In belugas (*Delphinapterus leucas*), substantial (10–15 dB) differences in temporary threshold shifts (TTSs) were observed between the first and subsequent experimental sessions in the same subjects. In the first session (naïve subject state), the TTSs produced by exposure to fatiguing noises were larger than the TTSs produced in subsequent sessions (experienced subject state). After one to two sessions, the TTSs stabilized. The baseline hearing thresholds did not differ between the naïve and experienced states. One possible explanation for this effect is that the animals learned to dampen their hearing during exposure to fatiguing noises and thus mitigate the impact of those noises.

Keywords Temporary threshold shift • Odontocetes

1 Introduction

The impact of loud sounds on the auditory system can result in permanent or temporary reductions of sensitivity that are known as permanent or temporary threshold shifts (PTSs or TTSs, respectively). Reversible shifts (i.e., TTSs) in odontocetes have been the subject of active investigation due to the assumption that a better understanding of the conditions that cause TTSs might help predict the conditions that cause PTSs. In a majority of these TTS investigations, multiple repetitions of the measurements were required to obtain significant data (e.g., Nachtigall et al. 2003, 2004; Finneran et al. 2005; Finneran and Schlundt 2010; Lucke et al. 2009; Mooney et al. 2009). Thus, the experimental subjects may have adapted to the sound exposure procedure,

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which would differentiate those animals from animals in the wild, i.e., the latter may be inexperienced with respect to exposure to fatiguing sounds.

During the last few years, we have collected data that show that the impact of fatiguing sounds on inexperienced belugas may differ from the impact on the same subjects after they have been exposed several times to TTS measurement procedures.

2 Materials and Methods

The study was conducted in 2011–2012 in the facilities of the Utrish Marine Station of the Russian Academy of Sciences (the Black Sea coast). The subjects were 5 young (2–3 years old, 3 male and 2 female) beluga whales (*Delphinapterus leucas*). Each of the animals was caught next to the Russian far east shore 1–2 months before it was transported to the Marine Station. The animals were housed in a 9 × 4 × 1.2-m pool filled with seawater.

Hearing thresholds both before and after exposure to fatiguing noises were measured using the auditory evoked potential (AEP) method. During the experiments, the animals were placed on a stretcher in a wooden tank (4.5 × 0.85 × 0.6 m) filled with seawater in such a manner that the dorsal surface of the head and the blowhole remained above the surface of the water. Suction-cup electrodes were applied for AEP recordings. The active electrode was fixed to the vertex of the head surface 7 cm behind the blowhole and above the surface of the water, and the reference electrode was fixed to the animal's back. The electrodes were connected, via shielded cables, to the input of a custom-made EEG amplifier that provided an 80-dB gain within the frequency range of 200 to 5000 Hz. The amplified signal was digitized and collected using a DAQcard-6062E data-acquisition board (National Instruments) and stored in computer memory.

The test sound stimuli were trains of tone pips. Each train contained 16 pips at a rate of 1000 pips/s. Each pip of the train contained 8 cycles of a carrier from 16 to 128 kHz enveloped by a cosine function so that the pip duration was from 62.5 μs at a carrier frequency of 128 kHz to 0.5 ms at a carrier frequency of 16 kHz. The pip trains were presented at a rate of 16 trains/s. The sound pressure level (SPL) of the pip trains was specified in decibels re 1 μPa of root-mean-square (rms) sound pressure over the 16-ms pip-train duration.

The fatiguing noises were half-octave band-filtered noises with center frequencies that ranged from 11.2 to 64 kHz. The SPLs of the noises were specified in decibels re 1 μPa of rms sound pressure.

Both the test and fatiguing sounds were digitally synthesized at a sample rate of 512 kHz and were digital-to-analog converted by the same DAQcard-6062E board, amplified, attenuated, and played through either an ITC-1032 (International Transducer Corporation) transducer (frequencies from 16 to 45 kHz) or a B&K 8104 (Bruel & Kjær) transducer (frequencies from 64 to 128 kHz). The transducer was positioned 1 m in front of the animal's head. To amplify and attenuate the test signal, a custom-made amplifier-attenuator with a 200-kHz passband was used. To amplify the fatiguing sounds, a CV-1800 amplifier (Cervin Vega) with a 65-kHz passband was used. The playback channel was calibrated before and after the experiments by positioning a calibrated receiving hydrophone (B&K 8103, Bruel & Kjær) near the animal's head.

For AEP recordings, 25-ms sweeps that were synchronous with the test stimuli were extracted from the brain-potential records. Five hundred sweeps that were triggered by the stimulus onset were coherently averaged on-line. For further analysis, a 16-ms segment of the averaged record (from 5 to 21 ms relative to the stimulus onset) containing a rhythmic AEP (the envelope-following response [EFR]) evoked by the pip-train stimulus was Fourier transformed on-line to obtain the response frequency spectrum. The magnitude of the 1-kHz spectral peak was taken as the measure of response magnitude.

Both the pre- and postexposure threshold dynamics were traced using an adaptive one-up one-down (staircase) procedure of stimulus variation. A record was considered to be response-present when the 1-kHz peak in the response spectrum was more than twice the magnitude of the spectrum components within the adjacent spectrum between 0.75 and 1.25 kHz; otherwise, the record was considered to be response-absent. Stimulus levels were varied in 5-dB increments/decrements. If a response was detected according to the criterion specified above, the subsequent stimulus level was decremented by 5 dB; if the averaged record was response-absent, the subsequent stimulus was incremented by 5 dB. Reversal points (transitions from stimulus level increase to decrease and vice versa) were selected, and the mean of each pair of adjacent reversal points (the local maximum and minimum) was assigned as an instant threshold estimate attributed to the middle point of the two corresponding time instants.

These experiments were not designed to determine differences between fatiguing noise effects across the naïve and experienced states of the subject because these differences were not anticipated before the study. The initial goal of the experiments was to investigate the dependence of TTS effects on the parameters of the fatiguing sound (Popov et al. 2013). Thus, for each of the subjects, the study design included (1) a baseline threshold measurement and (2) an investigation of the effects of exposure to noises with SPLs that ranged from 155 to 170 dB, center frequencies that ranged from 11.2 to 90 kHz, and durations that ranged from 19 to 6000 s. One experimental session was performed every day. Each experiment included a preexposure threshold measurement, an exposure, and a postexposure threshold tracing. The parameters of the exposure noises (center frequency, level, and duration) varied from session to session. The limited availability of subjects precluded multiple repetitions of all combinations of fatiguing noise parameters. However, several combinations were retested; among these, several combinations that were used in a subject's first experimental session were retested in the same subject later. These cases were selected to compare the effects of fatiguing noises on naïve and experienced animals.

3 Results

Test pip trains provoked EFRs when the stimulus levels were above threshold. The EFRs consisted of bursts of waves at the same frequency as the stimulus pip rate. In the majority of cases, a single 5-dB increment (or decrement) resulted in a transition from a response-absent to response-present (or vice versa) record when the stimulus levels were varied in the range near the threshold (as determined by the adaptive procedure). In some cases, this transition required changing the stimulus level by two steps (10 dB). In preexposure threshold tests, the mean of six instant threshold estimates was taken as the preexposure threshold. The session-by-session preexposure variations were less than ±5 dB relative to the baseline value.

After fatiguing noise exposure, the thresholds increased (the TTS effect). Either immediately after the end of the exposure or after a short delay (plateau), threshold recoveries were observed (Fig. 105.1). The postexposure threshold versus time dependence was approximated with a logarithmic regression line. The value of the regression line at the point 2 min after the offset of the fatiguing noise (the minimum time that was always sufficient for a threshold measurement) was taken as an arbitrary estimate of the immediate postexposure threshold. The difference between the post- and preexposures thresholds was taken as the TTS.

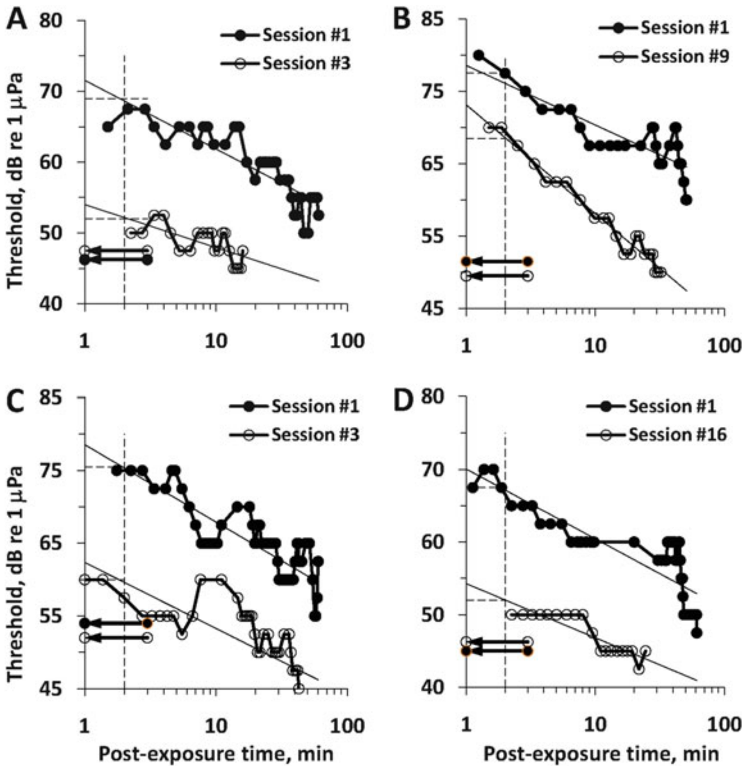

Fig. 105.1 Four cases of repeating tests of fatiguing noise effect. (**a**) Female, fatiguing noise of 32 kHz center frequency, 150 dB re 1 µPa level, 3-min exposure; test 64 kHz. (**b**) Female, noise 22.5 kHz, 165 dB, 3 min; test 32 kHz. (**c**) Female, noise 22.5 kHz, 170 dB, 3 min; test 32 kHz. (**d**) Male, noise 45 kHz, 150 dB, 3 min, test 64 kHz. Instant thresholds are presented as a function of postexposure time. *Diagonal lines* are log regression lines approximating the threshold versus time functions. *Dashed lines* mark thresholds at 2-min postexposure time. *Arrows* indicate preexposure thresholds for the corresponding sessions

Figure 105.1 presents four cases in which the effects of fatiguing noise were tested in the subjects' first experimental sessions and those subjects were retested in subsequent sessions (as described in Section 2; between these sessions, the subjects were exposed to noises with other parameters during the everyday sessions). In all the cases, repeating the test resulted in lower postexposure thresholds, whereas variation in the preexposure thresholds was negligible; i.e., in the first test, TTSs were greater than in subsequent retests when the parameters of the fatiguing noises remained constant. These differences ranged from 9 dB (Fig. 105.1b) to 17 dB (Fig. 105.1a). The preexposure thresholds differed little between sessions (these differences were restricted to ±2.5 dB).

After we noticed this effect, one more subject was still available for investigation. Thus, we examined whether TTSs decreased continuously over sessions or stabilized after a certain number of sessions. TTSs decreased in the second session compared with the first session; however, subsequent retests (up to a twelfth session) produced no further decreases in TTS (Fig. 105.2). In three retest sessions (second, third, and twelfth), postexposure thresholds varied from 76.8 to 79 dB SPL (mean ± SE: 77.6 ± 0.7 dB; 95% confidence range: 77.6 ± 3.1 dB), whereas in the first session, the postexposure threshold was as high as 86 dB SPL, i.e., 8.4 dB greater than the mean postexposure thresholds of later sessions. The preexposure thresholds differed little across all sessions (including the first session; mean ± SE: 54.5 ± 0.7 dB).

4 Discussion

Numerous investigations of TTS in animals (reviewed in Clark 1991) and humans (reviewed in Melnick 1991) have shown that repeated exposures to fatiguing sounds may result in cumulative, progressive increases in hearing thresholds. However, we are not aware of any data in the literature that indicate the possibility that the effects of exposure to fatiguing sounds are diminished after multiple sound exposures. The data presented herein support this possibility in belugas; in each animal's first test session, we observed a TTS that was greater than that evoked by the same fatiguing sound in later sessions. Subsequently, we refer to this effect as the "first-session effect." Notably, preexposure thresholds varied little across sessions; only postexposure thresholds differed between the first and the subsequent sessions. Thus, only the effect of noise exposure (i.e., the TTS) and not background hearing sensitivity varied across sessions.

These data were obtained from a limited number of available subjects. This limitation is a natural consequence of the specificity of the first-session effect; i.e., each subject could be considered to be naïve only once during the first session carried out with that particular individual (it is also possible that the animals should not be considered naïve not during the whole first session). Therefore, we cannot presently provide a reliable generalized statistical confirmation of the first-session effect. However, the number of repetitions performed in one subject allowed statistical

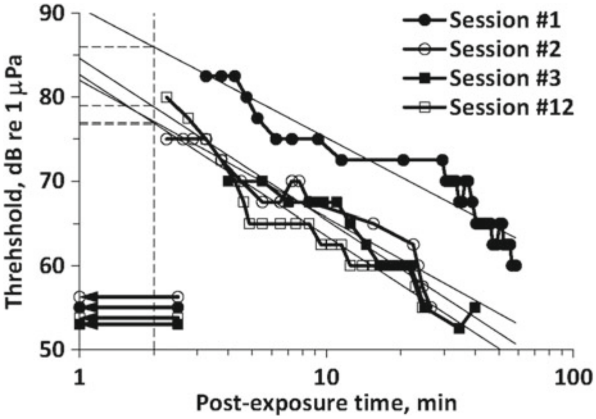

Fig. 105.2 Four repetitions of the temporary threshold shift test in one subject (male). Fatiguing noise of 22.5-kHz center frequencies, 170 dB re 1 µPa level, exposure duration 3 min; test frequency 32 kHz. *Diagonal lines* are log regression lines approximating the threshold versus time functions. *Dashed lines* mark thresholds at 2-min postexposure time. *Arrows* indicate preexposure thresholds for the corresponding sessions

evaluation of the first-session effect in that animal (see Fig. 105.2), and difference in postexposure thresholds between the first and subsequent exposures (8.4 dB) was several times larger than the 95% confidence interval (3.1 dB) of the mean of the second to twelfth sessions. So we consider the data presented herein as an indication that further investigation of the described phenomenon is reasonable.

If the first-session effect is further confirmed, we offer the following hypothesis to explain its mechanism. Recently (Nachtigall and Supin 2012, 2013), it was shown that whales are capable of learning to dampen their hearing when they anticipate the occurrence of a loud sound. It is reasonable to suppose that, in our experiments, the animals also learned to dampen their hearing to mitigate the impact of the fatiguing sound. This process would results in reductions in the magnitude of the TTSs evoked by the fatiguing sounds. Remarkably, after the first session, the TTS effect stabilized; i.e., the effect was not cumulative. This finding may be due to limitations of the available conditioned dampening, which was not more than 10–15 dB; this hypothesis is consistent with the data of Nachtigall and Supin (2013).

If this explanation of the effect is valid, it should be taken into consideration when experimental data are used to assess the effects of fatiguing sounds on marine mammals in the wild. Contrary to experienced experimental animals, naïve animals in the wild may be more susceptible to the impact of loud sounds.

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Chapter 106
Pile Driving at the New Bridge at Tappan Zee: Potential Environmental Impacts

Arthur N. Popper, Mark Moese, John Rollino, Justin Krebs, Roberto Racca, Bruce Martin, David Zeddies, Alexander MacGillivray, and Fred Jacobs

Abstract A new bridge will be constructed to replace the aging Tappan Zee Bridge over the Hudson River in New York. Construction will potentially result in hydroacoustic impacts to the local fish fauna. As a consequence, a substantial environmental impact analysis had to be conducted to obtain construction permits. This paper describes the process of environmental analysis and some of the results of the studies that led up to the final permitting. The process included modeling of pile-driving acoustics, analysis of river ambient noise, analysis of test piling, and observations on fish behavior during these tests.

Keywords Hudson River • Sturgeon • Hydroacoustics • Pile driving • Barotrauma

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1 The Tappan Zee Bridge

The 7-lane 4,881-m-long Tappan Zee Bridge (TZB), located ~40 km north of New York City, is an integral part of the New York State Thruway System. It carries 130,000–170,000 vehicles each day between Tarrytown, NY, on the eastern shore and Rockland County on the western shore of the Hudson River (see http://www.newnybridge.com/). The main span of the bridge is 369 m long and provides a maximum clearance of 42 m over the water. The rest of the bridge is a causeway that is ~5–10 m over the water and built on concrete piers supported with wooden pilings. The depth of the Hudson River at the TZB ranges from ~15 m under the main span to ~2 m toward the eastern and western shores.

The TZB opened in December 1955 and was designed to last 50 years. Repair and upgrade to meet modern engineering standards and to be able to withstand a 6.8 scale earthquake would essentially close the whole bridge for several years and the cost would likely be more than that of a new bridge. As a consequence, it was decided to build a new bridge just north of the current span. Construction started in mid-2013, and it is anticipated that it will be completed in ~4.5 years.

Development of the new bridge required extensive environmental impact studies to obtain permitting. This involved studies of the hydroacoustics associated with the impact and vibratory driving of more than 1,000 steel support piles. This paper presents an overview of the work done over the course of developing the Final Environmental Impact Statement (FEIS) and Biological Assessment (BA) and the subsequent studies after a more refined bridge design was developed. Additional papers (see Chapters 67 by Krebs et al. and 60 by Jacobs et al.) provide more specific details on various aspects of this project. A complete list of the documentation that resulted in the final approval for the new bridge is shown in Table 106.1.

Hydroacoustic analysis included modeling of the potential sound fields produced by driving various sized steel piles (Section 2.1) and a long-term study of the ambient noise soundscape (Section 2.2). This was followed in May 2012 by a Pile Installation Demonstration Project (PIDP) conducted to measure the sounds produced from steel piles driven along the intended bridge span (Section 3).

Analysis of PIDP data that used noise attenuation systems (NASs) to mitigate sound levels indicated that elevated sound fields did not extend as far as predicted by the modeling. As the project design developed, the PIDP data along with more detailed and specific information on construction methods, including the number and sizes of piles to be actually driven, were used to recalculate the potential impact to both the shortnose (*Acipenser brevirostrum*) and Atlantic (*Acipenser oxyrinchus*) sturgeon (Section 4). Finally, a number of permit conditions were imposed on the Permittee by federal and state regulators to ensure the protection of the two sturgeon species (Section 5).

Table 106.1 Progression of analyses for assessing effects of noise from pile driving during the new NY bridge project

Date	Deliverable	Significance	Reference/link
18 January 2012	Draft Environmental Impact Statement	Used noise models for piles ranging from 1.22 m (4 ft) to 3.05 m (10 ft) in diameter. Analysis based on $\mathrm{SEL}_{\mathrm{cum}}$ criterion of 187 dB re 1 $\mu\mathrm{Pa}^2\cdot\mathrm{s}$ and used worst-case bridge construction scenarios. Assumed impact hammers for entire length of pile driving	http://www.newnybridge.com/documents/deis/
April 2012	Revised Biological Assessment	Used $\mathrm{SEL}_{\mathrm{cum}}$ and noise model with a tiered approach (187, 197, and 207 dB re 1 $\mu\mathrm{Pa}^2\cdot\mathrm{s}$) for assessing impact to sturgeon	http://www.newnybridge.com/documents/feis/vol2/f-10-revised-biological-assessment-2012-04-12.pdf
22 June 2012	Final BO	NMFS used modeled noise and worst-case construction scenarios and relied on $\mathrm{SPL}_{\mathrm{peak}}$ to determine take. Project could result in onset of physiological effects for 70 individuals of each species	http://www.nero.noaa.gov/prot_res/section7/FHWA/FHWA%20Tappan%20Zee%20Bridge%20Replacement.pdf
25 July 2012	FEIS	FEIS relied on BO findings for assessing hydroacoustic impacts. Incidental take exceeded if more than 70 individuals affected, but only one can suffer mortality	http://www.newnybridge.com/documents/feis/
August to November 2012	Memo Demonstrating Fish Avoidance During PIDP	Analysis of abundance and movement of tagged sturgeon during pile driving supports use of $\mathrm{SPL}_{\mathrm{peak}}$ criterion	Krebs et al. (2012)
December 2012	Reevaluation Prepared	Analyses used PIDP field data and most recent bridge design that eliminated 3.05-m- (10-ft-) and 2.44-m- (8-ft-) diam piles. Smaller noise footprints and better attenuation by NASs than predicted by model	http://www.newnybridge.com/documents/dec-permit/permit-application-2013.zip
10 April 2013	Second BO	Used data from the Reevaluation and relied on $\mathrm{SPL}_{\mathrm{peak}}$ to determine take. Project could result in onset of physiological effects for 41 of each species	http://www.nero.noaa.gov/protected/section7/bo/actbiops/tappan_zee_bridge_replacement_2013_reinitiation.pdf

SEL_{cum} cumulative sound exposure level, SPL_{peak} peak sound pressure level, *NMFS* National Marine Fisheries Service, *FEIS* Final Environmental Impact Statement, *BO* biological opinion, *PDIP* Pile Installation Demonstration Project, *NAS* noise attenuation system

2 Early Project Stages

The initial scope of the project involved an analysis of the various species that could potentially be impacted in the Hudson River, with particular focus on the more than 100 fish species that inhabited or migrated through the regions of the current and proposed bridges (AECOM 2006, 2011). This analysis included sampling of fishes in the Hudson River and analysis of a decade of historical data to get a complete picture of the fish fauna. Because of the endangered status of the shortnose sturgeon and Atlantic sturgeon, the National Marine Fisheries Service (NMFS) required that comprehensive analysis efforts focus on these two species.

2.1 Modeling

A critical issue in defining the hydroacoustic effects was to have an understanding of the potential sound fields that could be generated by pile driving in the Hudson River. Although it was first considered that acoustic-monitoring data from other pile-driving projects (such as those done by the California Transportation Authority [Caltrans] and the Washington State Department of Transportation [WSDOT]) might be sufficient, it was determined that the combination of depths, substrates, pile sizes, and other factors for the proposed project made it impossible to determine if earlier data would be applicable. Accordingly, it was decided to construct an acoustic model of the proposed construction project, taking into consideration the unique conditions of the Hudson River. This work used a variety of propagation models and allowed construction of graphic representations of the likely extent of pile driving in the river, including presentation of the contours (isopleths) for sound exposure levels (SELs) that would exceed current or anticipated criteria for the onset of physiological effects on fish (Stadler and Woodbury 2009; MacGillivray et al. 2011).

Figure 106.1 presents two sets of contours for the cumulative SEL (SEL_{cum}) showing the modeled footprints for 3.05- and 1.22-m-diam piles. Significantly and reflecting the varied bathymetry and riverbed composition in this region of the Hudson River, the larger sound level contours for the 3.05-m piles do not describe clear circles but are instead anisotropic.

2.2 Ambient Noise Measures

To develop an analysis of the behavioral effects of pile-driving noise, it was important to consider the ambient noise in the Hudson River because such sounds could potentially mask detection of pile driving by resident fishes and thereby decrease behavioral effects. There were insufficient data in the literature to provide guidance on ambient-noise levels in the Hudson River. Accordingly, an ambient-noise study was performed in the vicinity of the TZB. This was designed to include measurements at a variety of locations and to obtain continuous recordings over several days

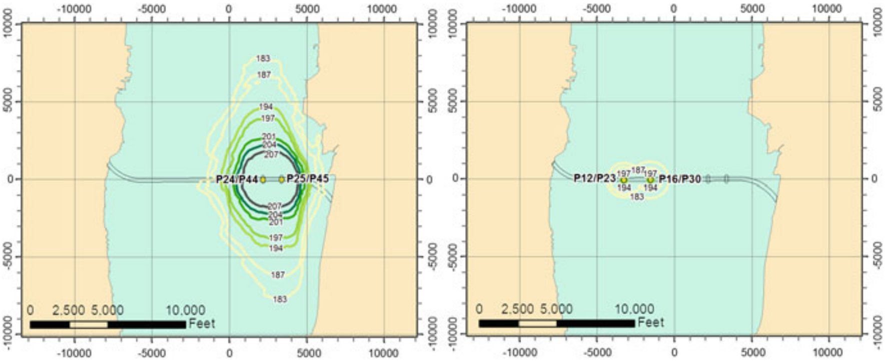

Fig. 106.1 Modeled cumulative sound exposure level (SEL_{cum}) contours for impact hammer driving near the current Tappan Zee Bridge (line across Hudson River) of four 3.05-m-diam piles for 2900 strikes (*left*) and four 1.22-m-diam piles for 3900 strikes (*right*) with BMP mitigation (piles indicated in *yellow* and designated with letter P). Distances are in feet (1 ft = 0.3048 m). The SEL_{cum} levels for each contour are re 1 μPa^2·s and indicate all energy for the duration of the pile driving. Modified from MacGillivray et al. (2011)

to assess sounds from the current bridge as vehicular traffic changed over the course of 24 h. In addition, long-term recordings were made from 12 August to 7 November 2010 to determine the seasonal changes in ambient noise (Martin et al. 2011).

The results showed a number of interesting properties of underwater noise in the study region of the Hudson River. First, the 1-min root-mean-square (rms) ambient sound pressure levels ranged from 85 to 145 dB re 1 μPa (10–16,000-Hz band). Levels above 125 dB re 1 μPa only occurred when a vessel passed close to a recorder. Second, the rms noise levels near the bridge were ~30 dB higher than the sound levels 3,000 m from the bridge. Sound levels near the TZB were nearly constant, with typical values between 115 and 125 dB re 1 μPa, whereas rms sound levels 3,000 m from the TZB were typically 85–95 dB re 1 μPa (Fig. 106.2). Pleasure boats and aircraft increased the sound levels in the frequency range of 100–10,000 Hz over small areas for periods of 2–5 min; commercial shipping, when present, increased the sound levels in the frequency range of 40–500 Hz over periods of 30–60 min. Interestingly, very low frequency sounds (<10 Hz) from trains along the east shore of the river entered the water through the substrate, suggesting that substrate propagation from pile driving could have an impact on the construction noise environment.

2.3 *Initial Calculation of Project Impacts*

The initial set of analyses performed for the FEIS and the BA were ultimately relied on by the NMFS in developing their allowable sturgeon “take” estimates for their Biological Opinion (BO) for the new bridge construction (NMFS 2012). These analyses were conservative in that they assumed that the entire length of the pile would be driven with an impact hammer. Gill net data collected during

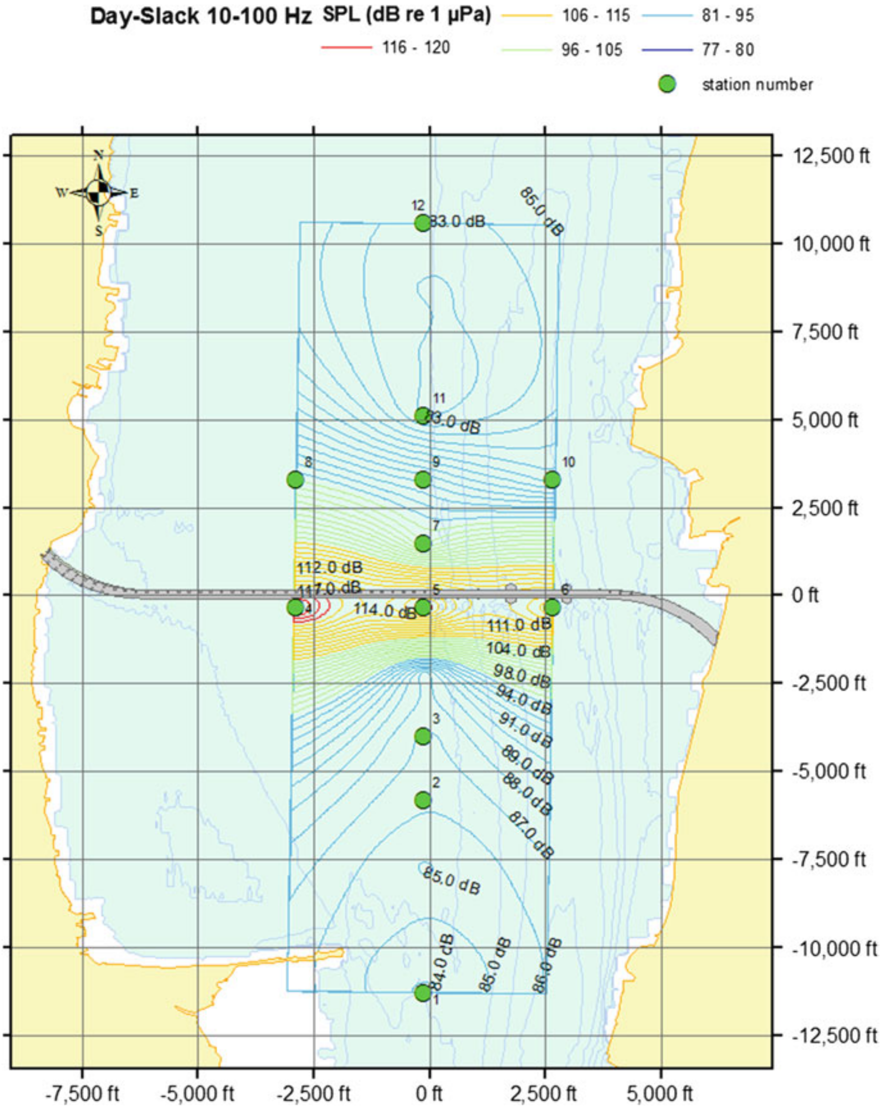

Fig. 106.2 Interpolated noise level contours of 15-min average broadband (10–100 Hz) sound pressure level (SPL) in daytime with slack tide on 10 August 2010 from 1,245 to 1,300 with an average flow speed of 0.42 ft/s. Green circles represent the sites of the recording devices. Modified from Martin et al. (2011)

2007–2008 were used to calculate the number of shortnose sturgeon collected per gill net per hour, develop a rate of sturgeon encountered per hour of sampling, and scale the gill net encounter rate to the area encompassed by the isopleth bounding the ensonified area. Because no Atlantic sturgeon were reported in the gill nets, 10 year of electric utility fish data (1997–2008) collected in the Tappan Zee region were used to estimate the abundances of juvenile Atlantic sturgeon and the seven most abundant finfish species. Based on results of the modeling, it was clear that 2.44- and 3.05-m-diam piles created the largest ensonified footprints. The statistical methods employed and the results of these technical analyses are more fully described in the Chapter 67 by Krebs et al. and in Appendix F-11 of the FEIS (http://www.newnybridge.com/documents/feis/); in every case, the number of fish potentially affected by pile-driving noise was only a very small fraction of the population.

A summary of the number of shortnose sturgeon potentially affected by pile driving for each week of the anticipated construction schedule, assuming a 10-dB reduction in SEL and peak sound pressure level (SPL_{peak}) through the use of NASs, was prepared for each of two bridge options and submitted to the NMFS. These summaries indicated that the hydroacoustic impacts of the two construction options had the potential to affect 70 and 43 shortnose sturgeon, respectively. Because they couldn't verify certain assumptions, the NMFS rejected the analysis approach developed for estimating the take of Atlantic sturgeon. The NMFS then reasoned that because no Atlantic sturgeon were collected in the gill net samples and the size of the Hudson River population of Atlantic sturgeon was considerably less than that for the shortnose sturgeon, the take estimates developed for shortnose sturgeon would be sufficient for determining Atlantic sturgeon take.

In making this assessment, NMFS used estimates of the effects based on the 206 dB re 1 μPa SPL_{peak} criterion rather than the 187 dB re 1 $\mu\text{Pa}^2\cdot\text{s}$ SEL_{cum} criterion, which has been relied on in previous BOs and was developed by the Fisheries Hydroacoustics Working Group (FHWG; reviewed in Stadler and Woodbury 2009). Hydroacoustic effects based on the SEL_{cum} criterion were also presented in the draft EIS (DEIS) for the bridge project. The SPL_{peak} is a measure of instantaneous peak noise exposure, whereas the SEL_{cum} is the total exposure received by an animal. The SEL_{cum} thereby reflects prolonged exposure to pile driving (or any sound), with the assumption that fish remain in ensonifed areas during pile driving for a period long enough to accumulate the required exposure. This change in the use of the selected criterion by NMFS may be of significance for assessing hydroacoustic effects for future bridge projects because application of the SPL_{peak} often results in a smaller ensonifed area than the SEL_{cum}; the reason this change was implemented is discussed more fully in Chapter by Jacobs et al.

3 PIDP

As part of the preparation for the bridge construction, the PIDP was conducted in the spring of 2012. Besides geotechnical testing, study elements of the PIDP consisted of monitoring the noise of the actual pile driving and an analysis of the potential physiological and behavioral effects on fish.

3.1 PIDP Noise Monitoring

Noise measurements were made during both vibratory and impact driving of 1.22-, 2.44-, and 3.04-m-diam steel piles in water of 5 m or less (Martin et al. 2012). The PIDP also tested the effectiveness of various NASs using bubble curtain technology. The results showed that all of the systems achieved $\mathrm{SEL}_{\mathrm{cum}}$ noise reductions of 10 dB or greater and reductions of 12.2–17.0 dB in the $\mathrm{SPL}_{\mathrm{peak}}$ depending on the NAS used, pile diameter, hammer type, and depth regimen.

The study also demonstrated that the signals from the piles propagated shorter distances than predicted either by the modeling study done for the project (MacGillivray et al. 2011) or by the NMFS practical spreading loss (PSL) model (Caltrans 2009; Stadler and Woodbury 2009); SPL versus range measurements from the test piles indicated that the propagation loss trend was 30–40 log R. The difference from the NMFS model is understandable because the NMFS model is based on a deepwater propagation loss model (15 log R) that is not applicable to the shallow Hudson River. The difference from the project modeling is more difficult to explain, but it may derive from the riverbed being more acoustically absorptive than was assumed in the model. In addition, the piles in the PIDP were surrounded by barges with 2–3-m drafts and these were not taken into account by the original modeling. The barges may have acted as an acoustic barrier that obstructed the transmission of sound from pile driving.

3.2 PIDP Fish-Monitoring and Damage Studies

As part of the PIDP, surveys were done to find any fish that came to the surface during the course of the pile-driving activities (AECOM 2012), including an analysis of tissues from any such fish (Popper and Casper 2012). In fact, over the 5-weeks period of PIDP pile driving, very few fish and no sturgeon were found dying or dead at the surface.

3.3 PIDP Analysis of Tagged Sturgeon

From 23 April to 20 May 2013, 155 tagged sturgeon were detected by three receivers located across the width of the river in the vicinity of the PIDP. Analysis of the data demonstrated that the likelihood of Atlantic sturgeon reaching the 187 dB re 1 $\mu\mathrm{Pa}^2\cdot\mathrm{s}$ $\mathrm{SEL}_{\mathrm{cum}}$ was extremely small during the PIDP (it only exceeded a probability of 1% for one fish and less than that for the others). During the PIDP, sturgeon avoided receiver detection areas in proximity of the impact pile-driving operations but did not appear to avoid these areas when vibratory hammering occurred. Accordingly, this PIDP analysis, which is discussed in greater detail in Chapter by Krebs et al. provides empirical evidence that the $\mathrm{SPL}_{\mathrm{peak}}$ criterion is the appropriate metric for assessing the potential hydroacoustic effects of impact hammering noise on sturgeon and supports the position taken by NMFS in their 2012 and 2013 BOs.

4 Reevaluation of Hydroacoustic Effects

After completion of the FEIS and the PIDP, a reevaluation of the hydroacoustic effects on sturgeon from pile driving was required. This reevaluation was necessitated by the selection of a design/builder who recommended a design that contained 916 piles plus 15 test piles, all 1.22 and 1.83 m in diameter, thereby eliminating the need for the 2.44- and 3.04-m-diam piles.

The number and size of the piles for the recommended design, the proposed pile installation schedule, specified hammering methods, and the PIDP empirical data were used to recalculate the number of sturgeon potentially affected by pile driving (AKRF and Popper 2012). The methodology for the impact assessment was similar to that used for the FEIS. The number of shortnose sturgeon subject to the potential onset of physiological effects during pile installation was predicted to be between 35 and 41 fish. NMFS concurred with these findings in a second BO using the recommended bridge design (NMFS 2013) and indicated that the incidental take would be exceeded if more than 41 shortnose sturgeon are observed stunned or injured or if more than one dead shortnose sturgeon is observed during pile driving. The NMFS again reasoned that because the Hudson River population of Atlantic sturgeon is less than the shortnose sturgeon population, 41 Atlantic sturgeon, representing three distinct population segments (Gulf of Maine, Mid-Atlantic Bight, and Chesapeake Bay), would also represent a conservative take estimate for Atlantic sturgeon, and only one individual could suffer mortality without the take being exceeded.

Other factors beside the elimination of the 2.44- and 3.04-m-diam piles, which reduced the high end of emitted noise levels, contributed to the lower take estimates than were calculated for the FEIS and the first NMFS BO. The empirical PIDP data showed the effectiveness of the bubble curtains, and the additional attenuation from barges surrounding the pile-driving operation reduced noise to more than the previously used measure of 10 dB. Also, the strikes required to drive many of the piles according to the recommended design would be less than previously modeled because of the increased use of a vibratory hammer during installation.

5 Additional Measures to Reduce and Monitor Hydroacoustic Impacts

The NMFS and the New York State Department of Environmental Conservation (NYSDEC) have imposed a number of permit conditions and “reasonable and prudent measures” to ensure that the pile-driving effects on sturgeon are minimized, avoided, and monitored. These included, among other things, use of NASs on all piles that are 1.22 m or greater in diameter; generally limiting the period of pile driving to no more than 12 h/day, except for rare circumstances; use of vibratory hammering wherever possible; maintaining a corridor where the sound level is below an $\mathrm{SEL_{cum}}$ of 187 dB re 1 $\mu\mathrm{Pa}^2{\cdot}\mathrm{s}$, totaling at least 1,524 m in river width at all times during impact hammering, of which any section cannot be less than 457 m in width; and pile tapping for an initial period to cause fish to move from the immediate area.

Acknowledgments We dedicate this paper to the memory of John Szeligowski. John was a prime mover in developing the environmental impact statements associated with construction of the Tappan Zee Bridge. He was a good and valued friend and colleague to all of the authors. John passed away before the start of construction, but his influence on the work and all of us was profound.

The work reported here was conducted for the New York State Thruway Authority. Opinions expressed in this paper are those of the authors and do not necessarily reflect the views of the Authority. We thank Helen Popper for careful editing of the manuscript.

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Chapter 107
Effects of Seismic Air Guns on Pallid Sturgeon and Paddlefish

Arthur N. Popper, Thomas J. Carlson, Jackson A. Gross, Anthony D. Hawkins, David Zeddies, Lynwood Powell, and John Young

Abstract Pallid sturgeon and paddlefish were placed at different distances from a seismic air gun array to determine the potential effects on mortality and nonauditory body tissues from the sound from a single shot. Fish were held 7 days postexposure and then necropsied. No fish died immediately after sound exposure or over the postexposure period. Statistical analysis of injuries showed no differences between the experimental and control animals in either type or severity of injuries. There was also no difference in injuries between fish exposed closest to the source compared with those exposed furthest from the source.

Keywords Fish • Anthropogenic • Noise • Damage • Lake Sakakawea

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1 Background

Very little is known about the effects of seismic air guns on the physiology of fishes. Moreover, all earlier studies on the effects of intense impulsive sounds on fishes (e.g., McCauley et al. 2003; Popper et al. 2005; Hastings et al. 2008), with the exception of recent pile-driving work (e.g., Halvorsen et al. 2012a, b; see Chapter 15 by Casper et al.), have focused on the effects on inner ear tissues and/or changes in hearing and have not systematically examined other nonauditory tissues. Because there is the potential that exposure to seismic air guns could affect mortality and nonauditory tissues, the current study assessed the effects of exposure to seismic air gun sounds on pallid sturgeon (*Scaphirhynchus albus*) and paddlefish (*Polyodon spathula*). In particular, the study was designed to provide quantified and statistically reliable data to evaluate the risk of immediate and/or delayed mortality as a result of exposure to impulsive sound produced by an air gun array of the same size that could potentially be used in a seismic survey of a lake.

The experiment was conducted in Lake Sakakawea, North Dakota, and involved placing fish in cages at different distances from the air guns and exposing them to different sound levels. Control animals were subjected to the identical treatment as the experimental animals but without exposure to sound.

2 Methods

The study used 3-years-old pallid sturgeon (41.4 ± 2.5 cm standard length; 224 ± 63 g) and 2-years-old paddlefish (46.8 ± 1.7 cm standard length; 352 ± 44 g) that were hatched and reared at the Garrison Dam National Fish Hatchery (GDNFH), Riverdale, ND. The fish were passive integrated transponder (PIT) tagged to enable individual identification, and care was taken to keep track of the exposure conditions and necropsy for each animal. For exposure, the fish were transported by truck to Lake Sakakawea, transferred to a boat, and then taken to the study site where they were placed in exposure cages that were constructed of 2.54-cm^2 braided knotless mesh mounted in a frame constructed of 2.54-cm PVC pipe. After exposure to the seismic source, the fish were retrieved from the cage and transported back to the hatchery where they were held for 7 days and then examined (see Section 2.5).

2.1 Fish Cage Location

Five cages were positioned at various distances from the array in Lake Sakakawea (Fig. 107.1). In addition, a sixth control cage was placed about 150 m south of the array. Control animals were treated identically to the fish in the sound-exposure cages except that the air gun array was not fired when control fish were in the water.

The five treatment cages were at 6 m depth for the pallid sturgeon and 2 m for the paddlefish (normal swimming depths for each species).

2.2 Experimental Design

During testing, three or four fish of one species were placed in each cage. The cage was then immediately lowered to the specified depth, exposed to one shot from the air gun array, and returned to the surface. By exposing only one cage at a time, it was possible to ensure that all fish were treated consistently and that all spent the same amount of time at depth before being exposed to air gun sounds. It should be noted that the physiological condition of the fish at the time of exposure, including whether the swim bladder was full at depth, was unknown other than that the fish were active and appeared healthy before being lowered to depth.

2.3 Air Guns

The air gun barge was outfitted with four Bolt Technologies Corporation (Norwalk, CT) Long Life Air Guns. Three air guns were 2,294 cm^3 and one was 3,277 cm^3, totaling 10,160 cm^3. The barge was placed at one end of the line of exposure cages (Fig. 107.1). The air guns were at 3 m depth during the experiments.

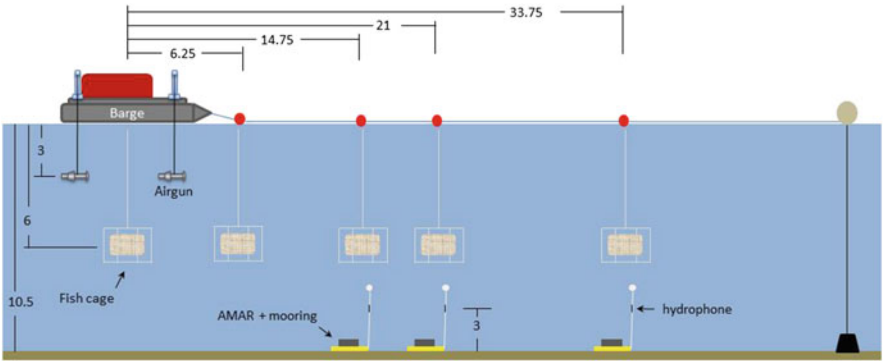

Fig. 107.1 Location of the five exposure cages relative to the air gun barge (*upper left*) and the air guns (just below the barge). Distances are in meters. The *red circles* represent the floats for the cages. The exposure cages were at a depth of 6 m for pallid sturgeon and 2 m for paddlefish. The black object at the far right represents the location of the control cage, which was at a depth of 3 m. The autonomous multichannel acoustic recorders (AMARs) and hydrophones were used to record all of the exposure signals for immediate and then later analysis

2.4 Acoustic Methodology

A comprehensive set of sound-exposure data was obtained using a combination of real-time and autonomous recording systems to measure sounds at the air gun barge and at the cages before and during the complete study (Fig. 107.1). This was necessary so that the effects on the fish (e.g., immediate or delayed mortality) could be correlated with the dose (sound) received by the fish. The sounds from each shot were monitored (via hydrophone) and the results were reviewed immediately after the shot to ensure that each was an acceptable replicate.

The maximum absolute peak sound pressure levels (SPLs) in the cages ranged from 231 dB re 1 μPa in Cage 1, which was located immediately below the barge, to 206 dB re 1 μPa at the furthest experimental cage (Cage 5), which was 33.75 m from the array. Respective values for root-mean-square (rms) SPL were 225 dB re 1 μPa at Cage 1–199 dB re 1 μPa at Cage 5, whereas the single-shot sound exposure level (SEL) for each air gun shot was 205 dB re 1 $\mu Pa^2 \cdot s$ at Cage 1 and 187 dB re 1 $\mu Pa^2 \cdot s$ at Cage 5. The rms SPL at the control site (without any seismic sound) was 105 ± 4.3 dB re 1 μPa, which represents the ambient noise level in the lake during the study.

2.5 Necropsy

Fish returned to the hatchery were kept in large tanks with flowing water. The animals were monitored every 12 h for 7 days postexposure. They were then euthanized, refrigerated for ~15 h, and necropsied. No animals died before euthanasia. Investigators doing the necropsies were not told the exposure of any individual fish.

Once a fish was removed from the refrigerator, the investigators made measurements of weight and size and recorded the tag number to correlate with exposure information. Necropsy procedures followed those developed by Halvorsen et al. (2012a, b).

Fish were immediately evaluated to assess bruising, hemorrhaging, and swim bladder condition. After the internal organs and body wall were evaluated, these organs were carefully removed or shifted to complete a more thorough examination of the swim bladder. Digital photographs were taken of all tissue as it was dissected and the internal condition of tissues of interest was recorded.

After evaluation of the swim bladder, the condition of the kidney was determined. The quantity of fat around the internal tissues was quite high in pallid sturgeon and so care was taken to not disturb the renal cavity and interconnecting vascularity while removing the fat. Removal of the fat allowed visualization of the kidney and swim bladder. Visualization of the swim bladder in paddlefish also required the removal of a layer of fat. This allowed the entire kidney to be seen.

2.6 Statistical Analysis

The experimental units in the study were individual cages, each with several fish inside. Each cage represents a binomial sample of n_i fish, of which xidied or had mortal injury. There were five sound-level classes (represented by Cages 1–5), with the level of sound decreasing with distance from the sound source. Each cage of fish received the sound generated by a single shot of the seismic array so that each cage of fish had a separate measure of sound exposure. Two sound covariates were used as independent variables to assess the relationship between sound level (exposure) and death/mortal injury (response). These were negative peak pressure (i.e., PEAK−) and SEL. There were also controls where fish received the same handling as the exposed fish except for exposure to sound. There were observations of death/mortal injury among the control fish so an Abbot's adjustment (Finney 1971) to the exposed fish was necessary.

3 Results

No animals died as an immediate result of exposure nor were there any mortalities for either species over the 7 days that the fish were held before being sacrificed. There were no significant differences in the level of tissue damage between exposed and control animals for either species or between specimens of the same species that were at different distances from the source.

4 Discussion

The single-shot exposure paradigm used in this study was selected because it was determined to be the best simulation of the probable exposure of individual fish during conduct of the proposed seismic survey strategy. In such a study, the seismic vessel carrying the air guns would move along preplanned transects where a single shot would be generated by the air gun array at each shot point. After a shot was completed, the vessel would move some distance to the next location where another shot would be fired. The distance traveled by the air gun vessel would, most likely, ensure that if a fish were exposed to two shots, one shot would usually be much higher in energy than the other so that any observed effect could be assumed to be a consequence primarily of the higher energy exposure. Thus, in the present experiment, it was concluded that only a single shot would be necessary to simulate the effective sound level to which fish would likely be exposed during an actual survey.

4.1 Overview of Findings

The initial goal in the experimental design was to develop a dose–response function whereby the levels of sound at fishes at different distances from the source could be quantitatively related to the response of the fishes to the sound exposure in terms of mortality during or within 7 days of exposure. However, a dose–response function could not be derived because no significant response of the test fish to seismic sound was detected and there were no differences in the observed effects between specimens at different distances from the source. Even at the highest sound levels, there was no mortality in fish suspended at the center of the air gun array where the greatest energy was found.

The results were contrary to the expectation that there would be mortality of fish exposed to the impulsive air gun sound, at least to sturgeon and paddlefish exposed at the highest sound levels (~224 dB re 1 μPa PEAK−, ~205 dB re 1 $\mu Pa^2 \cdot s$ SEL). The evaluation of mortality and mortal injury occurred over 7 days postexposure. At the completion of the study on day 7, the extent of swim bladder or kidney rupture or hemorrhaging did not differ significantly between exposed and control fish. Thus, it may be concluded that the sound levels from the seismic air guns used in this study, which is likely typical of many seismic surveys in lakes, were not sufficiently intense in terms of negative overpressure magnitude to cause mortality or mortal injury that could be associated with sound exposure within 7 days in sturgeon and paddlefish.

It is possible that under actual survey conditions the air guns would be fired repeatedly, possibly as frequently as once every few minutes, and so an alternative exposure scenario would have been to use multiple air gun shots. However, even if a fish were exposed to multiple air gun shots, the likelihood is that the sequence of exposures for freely swimming fish during the seismic survey would be a single high-level exposure followed by one or more exposures at much lower levels. The number of possible combinations of multiple exposures is very large when considering the uncertainties about the distribution of fish, their normal movement patters, and any possible response to sound. However, it is clear that because of the high rate of loss of sound energy (25log[*r*] transmission loss) with distance in shallow water, the total energy of exposure would almost certainly be dominated by the initial exposure.

4.2 Acclimation to Depth

Fish use their swim bladder to manage their buoyancy at different depths. To do this, they add gas to or remove gas from the swim bladder as they change depth. Fish add gas to the swim bladder either by gulping air at the surface of the water before they descend (physostomous species) or by using a special gland that they have as part of the swim bladder to pump air from the blood into the chamber (physoclistous species; see Stephenson et al. 2010). In either case, if the swim bladder is not properly inflated at the depth of the animal, the swim bladder does not help the fish maintain its position in the water column, thereby making it expend energy not otherwise required.

More important for this study, if the swim bladder is not fully inflated, the walls of the organ are not properly located with respect to the surrounding tissues. As a consequence, when the animal is exposed to an impulsive source, the walls do not move with the same amplitude or speed as they do in a fish with a normally inflated swim bladder. Thus, a fish that does not have proper swim bladder inflation for the depth at which it is exposed is less likely to show injuries than would a fish in which the swim bladder is properly inflated.

It is not clear whether the fish used in the study were physiologically acclimated to the exposure depth or not. The fish were lowered to depth as soon as they were placed in the cages and then exposed to sound within about a minute of reaching depth. As a consequence, the physostomous pallid sturgeon and paddlefish may not have had sufficient time at the surface to gulp the air they would need to have a properly filled swim bladder at 2 m depth (~120.9 kPa absolute pressure) in the case of the paddlefish and 6 m (~160.2 kPa absolute pressure) for the pallid sturgeon.

4.3 Implications of Results to Other Seismic Studies

It is concluded that although each seismic survey differs in the size of the air gun array, operational water depths, and the species potentially affected, the results from the present study suggest levels of impulsive seismic air gun sound to which adult fish can be exposed without immediate mortality. Pallid sturgeon and paddlefish with a body mass on the order of 200–400 g exposed to a received single-impulse SEL of 205 dB re 1 $\mu Pa^2 \cdot s$ did not die immediately or within 7 days of exposure and that the probability of mortal injury did not differ between exposed and control fish.

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Chapter 108

A Summary Comparison of Active Acoustic Detections and Visual Observations of Marine Mammals in the Canadian Beaufort Sea

Cynthia D. Pyć, Maxime Geoffroy, and Frank R. Knudsen

Abstract Fisheries sonar was used to determine the applicability of active acoustic monitoring (AAM) for marine mammal detection in the Canadian Beaufort Sea. During 170 h of simultaneous observation by marine mammal observers and active acoustic observation, 119 *Balaena mysticetus* (bowheads) and 4 *Delphinapterus leucas* (belugas) were visually sighted, while 59 acoustic signals of bowheads were detected by AAM operators. Observations and detection of seals were also recorded. Comparative results indicate that commercially available active acoustic systems can detect seals at distances up to 500 m and large baleen whales at distances up to 2 km.

Keywords Fisheries sonar • Marine mammals • Active acoustic monitoring

1 Introduction

Marine mammal observers (MMOs) monitor for marine mammals and other protected species in many jurisdictions during seismic surveys, decommissioning, and other oil and gas operations. Animal behaviors, inclement weather, and sea conditions can compromise visual detection. Towed passive acoustic monitoring (PAM) is increasingly advocated to detect vocalizing animals in addition to visual observation.

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However, detection distances for PAM are poorly understood. Also, PAM cannot detect animals that are not vocalizing and may not reliably detect animals calling at frequencies similar to those of vessel sounds, including most baleen whales. Assessment of active acoustic monitoring (AAM) equipment as a complement to more commonly used methods such as PAM and human observation has not been subject to extensive study to date, likely due to stakeholder sensitivity associated with all acoustic sources (Barlow and Gisner 2006).

2 Materials and Methods

The active acoustic study was conducted from the icebreaker CCGS Amundsen in the Beaufort Sea from 27 August to 4 October 2011. The fisheries sonar used was the SIMRAD SX90, with a frequency range from 20 to 30 kHz in 1-kHz increments. The cylindrical 256-element transducer enabled electronic tilting of the horizontal omnidirectional beam to vertically scan the water column. The SX90 has both horizontal and vertical transmission modes so that the AAM operator can see a target from both above and the side. Target echoes were displayed on the equipment screen, and speakers were connected to the system to listen for demodulated vocalizations recorded passively in the 20- to 30-kHz frequency range.

2.1 Survey Design

Four delimited areas were subject to dedicated SX90 studies in the southeastern Beaufort Sea and Amundsen Gulf. Survey areas were selected based on bathymetry, water mass properties, prevailing ocean currents, biological productivity, and the likelihood of encountering whales based on Fisheries and Oceans Canada aerial survey data collected over two decades (Harwood et al. 2010).

Out of a total of 290 h of sonar operations, 85 h were dedicated to SX90 surveys, most of which were conducted during the daytime (82%) to allow observation by MMOs and subsequent target validation using the SX90. In addition, the SX90 was operated for 205 h on an opportunistic basis, with 135 h spent in water deeper than 100 m. The MMOs and AAM operators simultaneously monitored for a total of 170 h. Vessel tracks are shown in Fig. 108.1.

Over the course of the study, MMOs were present on the vessel's bridge using reticle binoculars and Big Eyes to spot marine mammals. For all observations, the MMOs recorded the (1) time of sighting; (2) bearing, travel direction, distance, and location of marine mammals; (3) species, identification certainty, approximate size, and appearance of marine mammals; (4) number of individuals (including juveniles) observed and whether they resurfaced; (5) behavior of each individual; (6) presence and shape of blows; and (7) GPS position and picture file numbers where available. This information was logged and correlated with active acoustic detections during

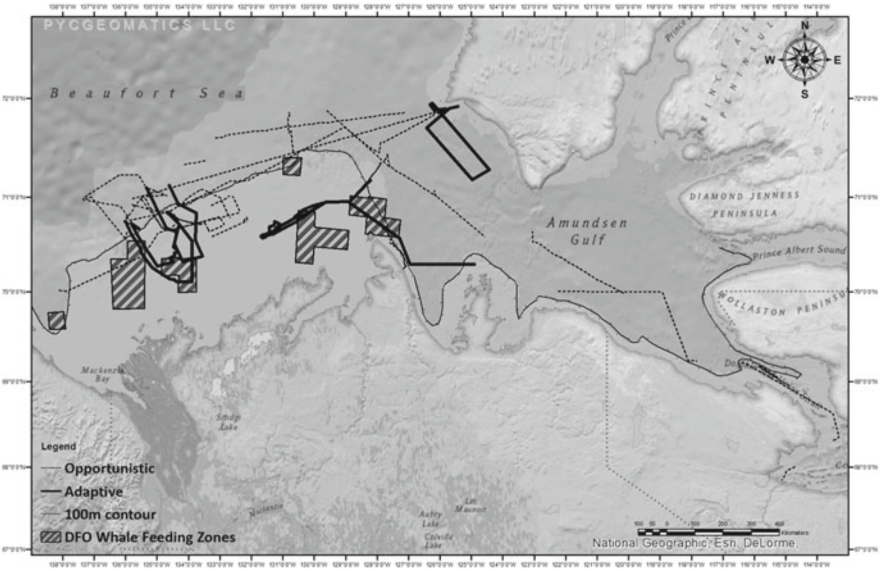

Fig. 108.1 Vessel tracks during adaptive and opportunistic surveys conducted from 27 August to 3 October 2011

data analysis as an aid in the establishment of acoustic recognition criteria. All sightings were communicated between the MMOs and AAM operators during the survey.

Survey protocol required vessel approach when the MMOs spotted marine mammals. For whales, the minimum distance of approach was 150 m and the maximum follow time was 10 min. As the ship moved away from the marine mammals, the in situ maximum detection range was noted.

3 Results

The MMOs observed 123 cetaceans and 31 pinnipeds (Table 108.1). The MMOs observed 64 cetaceans, including 60 bowhead whales and 4 beluga whales, at distances <2,000 m, the maximum range of the SX90 as dictated by oceanographic properties. An additional 59 bowhead whales were observed by the MMOs at distances beyond 2,000 m. Of the 60 bowhead whales observed by the MMOs within the range of the SX90, 59 were also detected with the SX90 (Table 108.1). All of the bowhead whale sightings beyond 500 m occurred when an acoustic duct was present. One observation of a group of 4 belugas at 900 m went undetected by the SX90.

Of the 31 pinnipeds observed by the MMOs, 22 were ringed seals, 2 were bearded seals, and 7 could not be identified at the species level. All MMO seal observations occurred at distances closer than 900 m. Thirteen of the ringed seals and two of the bearded seals were also detected by the SX90.

Table 108.1 MMO observations and SX90 horizontal detection ranges of marine mammals

Survey area	Bowhead whales		Beluga whales		Ringed seals		Bearded seals		Unknown seals	
	SX90	MMO	SX90	MMO	SX90	MMO	SX90	MMO	SX90	MMO
SA-1/SA-4	47	82	–	4	6	6	2	2	–	–
SA-2	6	17	–	–	5	6	–	–	–	–
SA-3	–	–	–	–	–	7	–	–	–	4
SA-5	–	N/A	–	N/A	–	N/A	–	N/A	–	N/A
Opportunistic	6	20	–	–	2	3	–	–	–	3
Total	59	119	0	4	13	22	2	2	0	7

MMO marine mammal observers, *N/A* periods of time when MMOs were not present

4 Discussion

4.1 SX90 Detections and Detection Range

This work provides evidence that the SX90 can reliably detect bowhead whales in the Beaufort Sea at distances relevant to some monitoring and mitigation programs. This is consistent with other studies on marine mammal detection using the SIMRAD SP90, in which orca whales were detected at ranges up to 1,500 m (Knudsen et al. 2007). During the Beaufort SX90 study, the presence of an acoustic duct likely facilitated long horizontal range detections.

In addition to technology limitations, time spent at depth varies by marine mammal and this affects detectability. For example, Mate et al. (2000) previously reported that bowhead whales spend 87% of their time at depths <100 m during the summer in the Canadian Beaufort Sea. Heide-Jørgensen et al. (1998) reported that belugas in the Canadian archipelago spend on average 40% of their time at the surface (<5 m), with dive durations of 7–8 min. Thus, in the Canadian Beaufort Sea, any large whale spending a few minutes at a distance <2,000 m from the ship will probably be detected on the horizontal view (tilted 1–2° below the surface).

Within the range of detectability, background noise/backscatter limited detection at distances between 300 and 550 m at water depths shallower than 300 m where reverberation clutter obscured all possible whale echoes (Fig. 108.2). This potentially limits the applicability of this type of sonar as a monitoring tool in shallow depths. Technical enhancements related to a real-time sonar ray-tracing model output of transmission loss and reverberation during monitoring are required to improve the usefulness of active acoustics in shallow water environments.

4.2 Equipment Reliability and Limitations

A total of 290 h of AAM in the Canadian Beaufort Sea appears to represent the largest AAM of marine mammals using commercial fisheries sonar (Geoffroy et al. 2012). The SX90 uses a robust interface and is simple to operate with practice.

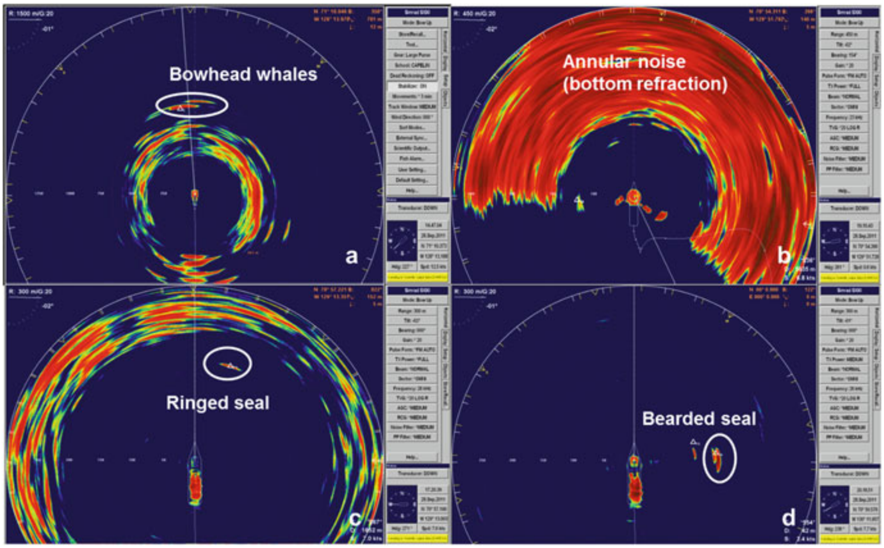

Fig. 108.2 Signature of bowhead whales detected in the acoustic channel at a range of ~1,500 m (**a**); annular noise from bottom refraction (**b**); a ringed seal detected in the "normal" beam at a range of ~150 m (**c**); and a bearded seal detected in the "normal" beam at a range of ~150 m (**d**)

The equipment was hull mounted in this instance and therefore did not suffer from operational issues often associated with towed PAM systems nor did AAM operators encounter hardware/software interface issues.

5 Conclusions

Results from the work show that the SX90 can detect marine mammals at a distance up to 2,000 m in the Canadian Beaufort Sea when desirable water column characteristics are present. During the 2011 survey, the acoustic duct that enabled long detection ranges was present in nearly 90% of the SX90 recordings. The reliability of the equipment and the accuracy of detection were confirmed in situ and were consistent with other surveys using active acoustic methods to study marine mammals.

Although the SX90 did not detect all of the marine mammals seen by MMOs, it does not suffer from some of the limitations that are unavoidable when using MMOs alone. Most notably, the SX90 can operate in conditions of darkness and low visibility, provided that reasonable oceanographic conditions are present.

Under some circumstances, the effectiveness of monitoring for mitigation purposes during industrial operations could be increased by combining techniques as done during the study described here. An approach that combines MMOs with systems such as the SX90 may also provide an improved understanding of potential changes in the distribution of vocalizing whales responding to industry sounds (Stein 2011).

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Chapter 109
Use of Preoperation Acoustic Modeling Combined with Real-Time Sound Level Monitoring to Mitigate Behavioral Effects of Seismic Surveys

Roberto Racca and Melanie Austin

Abstract Underwater acoustic modeling is often used to estimate the injury radius around a seismic exploration source; only occasionally has it been applied to the mitigation of behavioral effects, where the safety boundary may extend to many kilometers. Such a mitigation strategy requires precise estimation of the sound field for many source locations and likely entails field validation over the course of the operation to ensure that mitigation regions are accurate. This article reviews the enactment of such an approach for a seismic survey off Sakhalin Island and examines how similar principles may be applied to other surveys under suitable conditions.

Keywords Air gun • Marine mammal • Impulse noise • Sakhalin Island

1 Introduction

Underwater geophysical sensing technologies based on the use of impulsive sound from air gun arrays to image subbottom layers remain, to date, the prevalent method for hydrocarbon exploration, although alternative approaches such as the use of vibratory seismic sources (vibroseis) are under advanced development and operational testing. Although the potential for air guns to directly harm marine life is low except at a relatively close range, the use of these sources can result in behavioral responses over large areas as reported widely in the literature (see review by Nowacek et al. 2007).

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It is common practice, and very often a regulatory requirement, to conduct presurvey numerical modeling to estimate the range from the source at which injury can occur, whereby shutdown radii are implemented for mitigation. In that context, the model-based estimate is usually verified and possibly adjusted through a dedicated, one-time measurement trial at the beginning of the survey involving a few acoustic measurement sites at various offsets from a prescribed navigation line along which the source is operated. Analysis of these measurements is most often performed from recorded acoustic waveform data after retrieval of the acoustic recorders. There would be considerable added complexity and little benefit in deploying a longer term, telemetered acoustic-monitoring infrastructure to allow the ongoing verification of the effective threshold radii over the course of the survey.

A very different situation occurs if the requirement is to monitor and mitigate noise exposure from a seismic survey to minimize or avoid behavioral disturbance. This entails a much larger exposure area that in terms of implementing a protection zone may be more practically considered as an overall swath for a given seismic line than as a moving region centered at the seismic source. Depending on the geometry of the seismic survey, distribution of the animals of interest relative to the coastline or other bounding features, and the available stations (whether land or vessel based) from which observation can occur, different strategies are possible for the delineation and monitoring of the protection zone.

The common element to any such approach is the requirement for acoustic modeling to provide the estimated regions where ensonification above a selected sound level threshold will occur. In an idealized situation where the results of the modeling could be assumed to give an accurate representation of the acoustic footprint, a single modeling configuration for each seismic survey line would suffice and there would be no need for field verification through acoustic monitoring. In practice, the propagation conditions can only be estimated in advance to within a range of possibility, and some acoustically relevant properties (such as temperature and salinity in the water column) may change over the course of the survey. This precludes the possibility of a using a single set of predefined parameters for modeling the entire operation. Instead, for each seismic line, a library of footprints based on a reasonable range of acoustic environmental parameters (primarily the water sound velocity profile) can be precomputed. In the field, the case that most closely reflects the current acoustic conditions can be selected by matching model estimates of air gun array pulse levels to actual measurements from telemetric acoustic stations at a few fixed sampling sites in the initial minute or so of a line acquisition. An even higher degree of field validation may involve not only the initial selection of the most closely matching model case but also the real-time verification throughout the acquisition of a line that the acoustic pulse levels being received at the sampling locations continue to lie within a set tolerance of the model prediction. This ensures that the estimated footprint remains applicable or allows for its updating if necessary. The latter strategy implements an essentially closed-loop mitigation approach that provides the greatest possible confidence in the estimation of the behavioral threshold boundary for each line in a survey, even in case of rapidly changing (spatially or temporally) propagation conditions.

The full extent of the measures described above was implemented for a seismic survey conducted in 2010 near a marine coastal region that is part of the life cycle of a population of whales whose survival is considered at risk. Because of the importance of avoiding adverse behavioral impact on the animals, years of research and consultation among a team of independent experts led to the development and refinement of the acoustic estimation concepts described here. Section 2 examines the details of that implementation as a case study of the more general approach.

2 The 2010 Astokh 4-Dimensional Seismic Survey Case Study

2.1 Overview

The case study presented here involves a 4-dimensional (4-D) seismic survey conducted for the Sakhalin Energy Investment Company Ltd. offshore of the Astokh region of northeastern Sakhalin Island in the Russian Far East (Fig. 109.1). This area includes the summer feeding grounds of *Eschrichtius robustus* (western gray whale), an endangered population estimated at 134 individuals at the time of the survey. The intent of the monitoring and mitigation plan was to reduce noise disturbance to western gray whales and to limit their exposure to noise on their feeding grounds. The survey occurred from 18 June to 2 July 2010. In total, 35 survey lines were acquired from a vessel towing two 2,620 in.^3 air gun arrays that emitted sound pulses alternately as the source vessel transitted each line. Some lines were acquired more than once, wholly or in part.

Before and throughout the survey, a multidisciplinary team of scientists, supported by the oil and gas company, implemented a sophisticated noise exposure monitoring and mitigation plan (International Union for Conservation of Nature [IUCN] 2010). As described above, the plan consisted of three key components: (1) preseason estimation of sound propagation using numerical acoustic models, (2) real-time monitoring of underwater sound levels using telemetered acoustic data, and (3) coupling of acoustic and visual data using specialized geographic information system (GIS)-based software to plot visual sightings data relative to modeled sound-level contours.

At the foundation of the mitigation plan were the results of extensive preoperational numerical modeling of the acoustic footprint of the seismic air gun array. Two types of acoustic model results were used in the field for distinct purposes: (1) sequences of estimated per-pulse sound exposure level (SEL) values at the seafloor, indexed by source position along a survey track, at the sites of nine bottom-deployed acoustic telemetry stations. These sequences were used by an acoustics-monitoring team in the field to select a model case that best matched the pulse levels received in real time. Thereafter, the acoustics team monitored the telemetered data to verify the continued accuracy of the model estimates as the seismic vessel progressed along the line; and (2) static outline maps of the estimated shoreward extent of sound above the behavioral sound threshold for each survey line. The region where such outlines overlapped with the key gray whale feeding area defined the gray whale protection zone. These outlines, overlaid on specialized GIS-based software

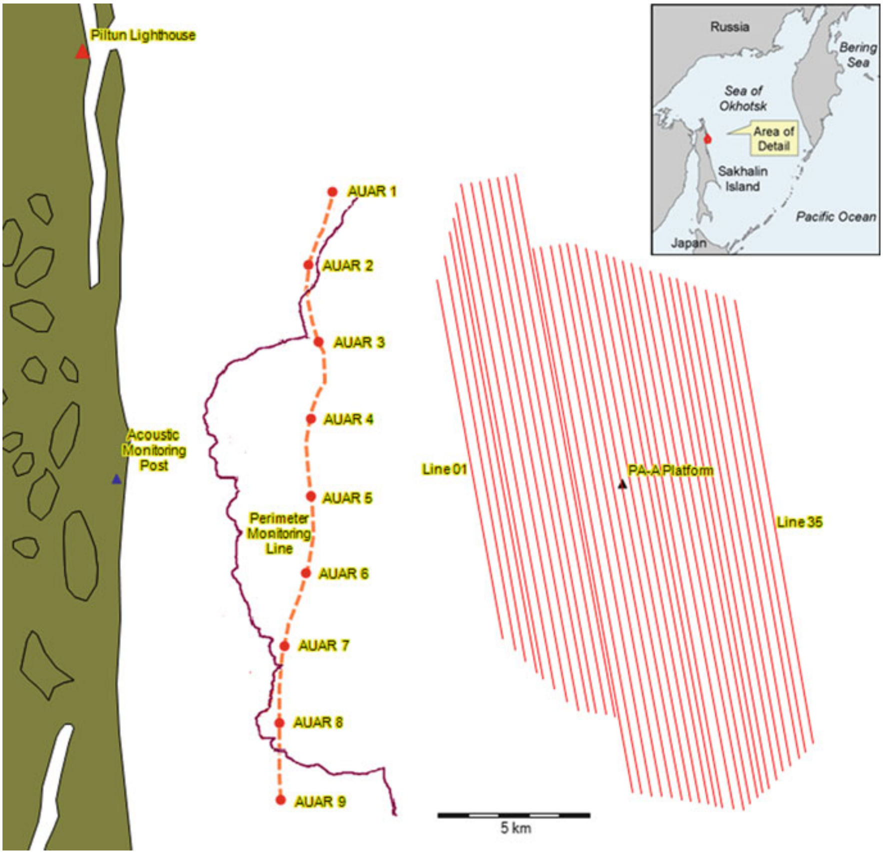

Fig. 109.1 Map of the seismic survey region showing the nine acoustic telemetry buoys, the perimeter monitoring line, and a sample outline of the shoreward extent of the behavioral sound level threshold. AUAR, autonomous underwater acoustic recorder

for cetacean tracking, provided observer teams with a reference boundary that defined whether a located animal was in a region where sound levels were considered liable to elicit behavioral disturbance.

2.2 *Sound Propagation Modeling*

The air gun source-level model AASM (MacGillivray 2006) was used to generate a directional sound signature for the survey air gun array configuration. The directional levels were input to JASCO Applied Sciences' parabolic equation acoustic propagation model MONM (described by Austin 2012) to generate long-range sound-level contours, maximized over depth, for several tens of source points along each seismic survey line. The shoreward envelope (maximum extent) of the contours from all source points to a prescribed behavioral threshold of 156 dB re 1 μPa^2·s per-pulse SEL (IUCN 2010) defined the static outline of the protection zone for that seismic line (shown in Fig. 109.1). Only the shoreward envelope was important because the most utilized gray whale feeding grounds lay inshore from the survey area.

To account for variability of sound propagation conditions and model uncertainty, a collection of model cases that covered a range of potential acoustic environments and sound level offset adjustments was generated. This preparatory work resulted in a comprehensive library of predictive model cases from which to draw during real-time operations.

2.3 Real-Time Acoustic Monitoring

Real-Time Acoustic Data Collection

Real-time acoustic data were streamed from a set of autonomous acoustic measurement instruments deployed along a line roughly parallel to the shore at about the 20-m bathymetry contour, distributed over 20 km in the north–south direction. This perimeter monitoring line (PML) was based on the best available historical estimation of the distribution bounds of the western gray whale population in the region at the time of the survey (IUCN 2010). Nine digital autonomous underwater acoustic recorders (AUARs; 16-bit, 30-kHz sample rate) were installed on the seafloor with tethered radio buoys that transmitted subsampled (~4-kHz rate) waveforms. These units were built, deployed, and maintained by the acoustics group at the Vladivostok-based Pacific Oceanological Institute (POI).

The telemetered acoustic data were received and processed by a shore-based acoustics-monitoring team from a laboratory hut located halfway along the length of the PML to optimize radio transmission ranges. Directional dipole antennae mounted on tall masts and trained on the bearing of each AUAR provided good radio-frequency reception gain, maximizing sensitivity to the signals broadcast by the AUARs via lower gain, omnidirectional whip antennae. The VHF-band radio signals were tuned to commercial marine receivers and the modulated audio output was processed through digital decoders designed by the POI that reconstructed the original acoustic pressure time series. The nine channels of digital data were archived to disk and processed by a front-end computer for spectral characterization and then streamed in 1-min batches over a local network to an independent system for air gun array pulse-level analysis and model verification.

Model Case Selection and Real-Time Verification

The acoustics field team monitored the pulses received from the PML stations on a multichannel display that also indicated the successful detection and sound-level processing of each pulse. When the seismic vessel reached the start of the line, with the air gun array in normal operating mode, it cued by radio the onshore acoustics-monitoring team, which would then begin logging the received pulse levels from the AUARs. The pulse levels from the first minute of acquisition (usually around 6–7 readings per channel) at the three PML stations closest to the start of the survey line were used to select the best model case for that line run. This was done with a spreadsheet application that compared the average measured pulse levels at the three PML stations with the predicted levels at the same sites from model scenarios corresponding to standard (base), low-, and high-sound propagation regimens. The software would display the propagation regimen and a decibel offset (jointly referred to as a "model case") that resulted in the smallest residual between the forecast and measured start-of-line levels. The process of selecting the appropriate model case for the active line typically took less than 5 min.

After the model case was selected and communicated (see below), the acoustics-monitoring team would proceed with real-time verification of its ongoing suitability. A custom software application was used to plot a real-time chart of the received pulse-level traces at all the PML stations as a function of the progression of the source vessel along the line. The application screen would also show the corresponding estimated pulse-level trace for the active model case at a user-selected PML station, allowing a direct comparison between model and measurement at a given sensor. In a typical line run, the acoustic-monitoring team would sequentially select the telemetric sensor most proximal to the current position of the seismic vessel for verification because that telemetric sensor would be measuring the dominant across-track (broadside) beam of the air gun array that shaped the reach of the estimated shoreward sound level boundary. The active model case complied with the mitigation plan directives if the measured pulse-level trace, exclusive of jitter and transient oscillations, remained solidly within a tolerance band of +3 dB from the modeled trace. A failing of this condition would have meant that the active model case was no longer applicable and would have to be updated with another case from the library. Figure 109.2 is an example of the type of display the acoustic-monitoring team viewed in the field to track the agreement between measured and modeled pulse levels.

2.4 Integration with Visual Sightings

Having selected the active model case for a line, the acoustic-monitoring team would immediately broadcast it to three visual observation teams (two based at tower platforms on the shoreline and one on a spotter vessel) through an established protocol of two-way radio communication relays. The observation teams would then retrieve, from a locally stored database, the corresponding premodeled protection zone boundary, which would be displayed as a map overlay in a specialized cetacean-tracking software application. This software processed visual observation fixes from theodolites and reticle binoculars into georeferenced coordinates on a

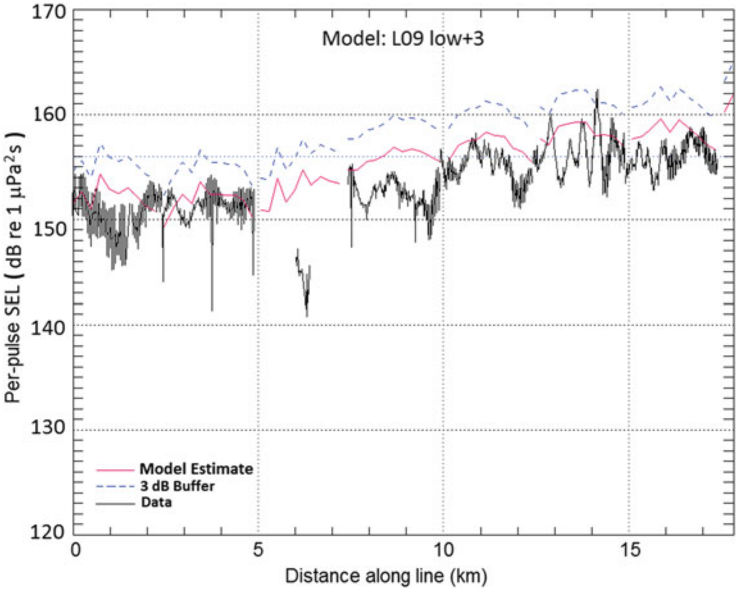

Fig. 109.2 Screen capture from the software used by the acoustics-monitoring team in the field showing the agreement between measured (*black*) and modeled (*red*) pulse levels during acquisition of seismic line L09, along with the +3-dB tolerance band (*dashed blue*). *SEL* sound exposure level

map, allowing the teams to assess within seconds whether a whale sighting was within or outside the estimated region of potential behavioral effect and react according to the response procedures in the monitoring and mitigation plan.

2.5 Outcome

Compliance with the monitoring and mitigation plan resulted in behavioral safeguard shutdowns of the air gun array on 3 out of 59 occasions when whales tracked by theodolite were located within the protection zone. Four survey lines were interrupted when deteriorating visibility precluded visual coverage of the protection zone by the observation teams; an additional two lines being acquired in darkness were ended when they reached the point where the modeled threshold boundary encroached into the feeding grounds. Incomplete lines were later resurveyed wholly or in part.

In the course of the survey monitoring, there appeared to be a considerable shift in the model case selection, which suggested a transition between different propagation regimens as the operation progressed. The trend in the variation of the model cases was later found to correlate well with a change in the sound velocity field distribution shown in hydrological data collected by the POI during the seismic survey (Rutenko et al. 2012). This critical change in the propagation conditions would have been ignored in the mitigation had real-time monitoring and model validation not been a part of the plan.

The survey was completed in 15 days of acquisition, which was within the expected time frame when accounting for delays due to weather and technical issues. As such, this case study exemplifies the implementation of a rigorous monitoring and mitigation program that still did not restrict the successful and timely completion of the seismic survey.

3 Generalization to Other Seismic Surveys

A few unique characteristics of the Astokh 4-D survey facilitated implementation of the comprehensive mitigation plan described. First, the availability of multiyear data on western gray whale distribution patterns was essential in delineating the critical region of the feeding grounds. The fact that this region was restricted to a relatively confined area between the survey lines and shore enabled focused observation efforts. In optimal weather conditions, complete coverage of the protection zone was readily achieved with a small number of observers at just three visual monitoring stations. The proximity to shore also allowed the use of a single fixed telemetry reception point with high-gain, tower-mounted directional antennae; it would have been difficult to maintain simultaneous radio coverage of nine telemetry buoys spread over a 20-km front from a vessel-based reception platform. This real-time aspect of the monitoring program, supported by the extensive library of model alternatives, provided an unprecedented capability for immediate adaptation to current acoustic conditions.

Not all of the above conditions will easily be found in such a favorable combination in other seismic survey scenarios where a similar approach would be appropriate. It should be recognized, however, that the very characteristics that may contribute to enhancing the potential risk to the population associated with behavioral disturbance, such as a narrow feeding area bookended between the coastline and the seismic survey, may also provide the advantageous monitoring conditions that enable the implementation of an advanced mitigation plan. Put another way, the greater the geographic freedom of the population from landmasses and other distribution constraints such as preferred habitats, the lesser the requirement may be for the degree of detailed tracking whose feasibility, as seen in the case study, also hinges on that spatial confinement. Having established that a requirement does exist for model-based behavioral disturbance mitigation, individual aspects of the overall strategy discussed here may be adopted, omitted, or variously adapted to meet the conservation objectives and operational constraints. In situations where it is acceptable to have a greater tolerance on the effective bounds of the protection region, it may be sufficient to implement a model case selection scheme based on pulse-level measurements at line starts without the subsequent verification of continued accuracy requiring a full perimeter monitoring line flanking the seismic survey area. In a scenario where shore-based visual monitoring of the modeled protection region boundary is impossible, localization of whales from one or more vessels through reticle binoculars provides a less precise but viable alternative to land-based theodolite stations; the software used in the case study has the ability to georeference observations relative to a moving platform if the GPS location and heading of the latter are provided as real-time inputs.

4 Conclusions

The successful implementation of the acoustic monitoring and mitigation plan for the seismic survey presented as a case study demonstrates the feasibility of an approach providing good confidence that the animals of interest are not exposed to sound levels exceeding a given threshold. This approach to behavioral impact mitigation based on precomputed modeling and field validation of threshold sound level boundaries can be realized under a variety of conditions and should be considered as a viable strategy when warranted by the vulnerability of a population to subinjury disturbance levels.

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Chapter 110
Potential Competitive Dynamics of Acoustic Ecology

C.A. Radford and J.C. Montgomery

Abstract The top predators in coastal marine ecosystems, such as whales, dolphins, seabirds, and large predatory fishes (including sharks), may compete with each other to exploit food aggregations. Finding these patchy food sources and being first to a food patch could provide a significant competitive advantage. Our hypothesis is that food patches have specific sound signatures that marine predators could detect and that acoustic sources and animal sensory capabilities may contribute to competition dynamics. Preliminary analysis shows that diving gannets have a distinct spectral signature between 80 and 200 Hz, which falls within the hearing sensitivity of large pelagic fishes. Therefore, we suggest that diving birds may contribute to the sound signatures of food aggregations, linking competition dynamics both above and below the water surface.

Keywords Underwater acoustics • Whales • Birds • Fish • Sound signatures

1 Introduction

Remote sensing from space has generated huge progress in our understanding of terrestrial systems and the ocean's surface. However, space-based remote sensing cannot characterize the water column below the ocean's surface, although active acoustics has been used for years to map the seafloor (Montgomery and Carter 2011). Remote passive acoustics that targets the water column has equal potential to contribute to marine science and there is growing recognition of the importance of passive listening systems to characterize the ocean sound sources and monitor marine ecosystems (Southall and Nowacek 2009).

The rapidly developing area of acoustic remote sensing is also being matched by new discoveries of the ways in which marine animals use ambient underwater sound as an orientation and settlement cue. The Leigh Marine Laboratory has been a pioneer in this field, providing the first experimental evidence that fish, crustaceans,

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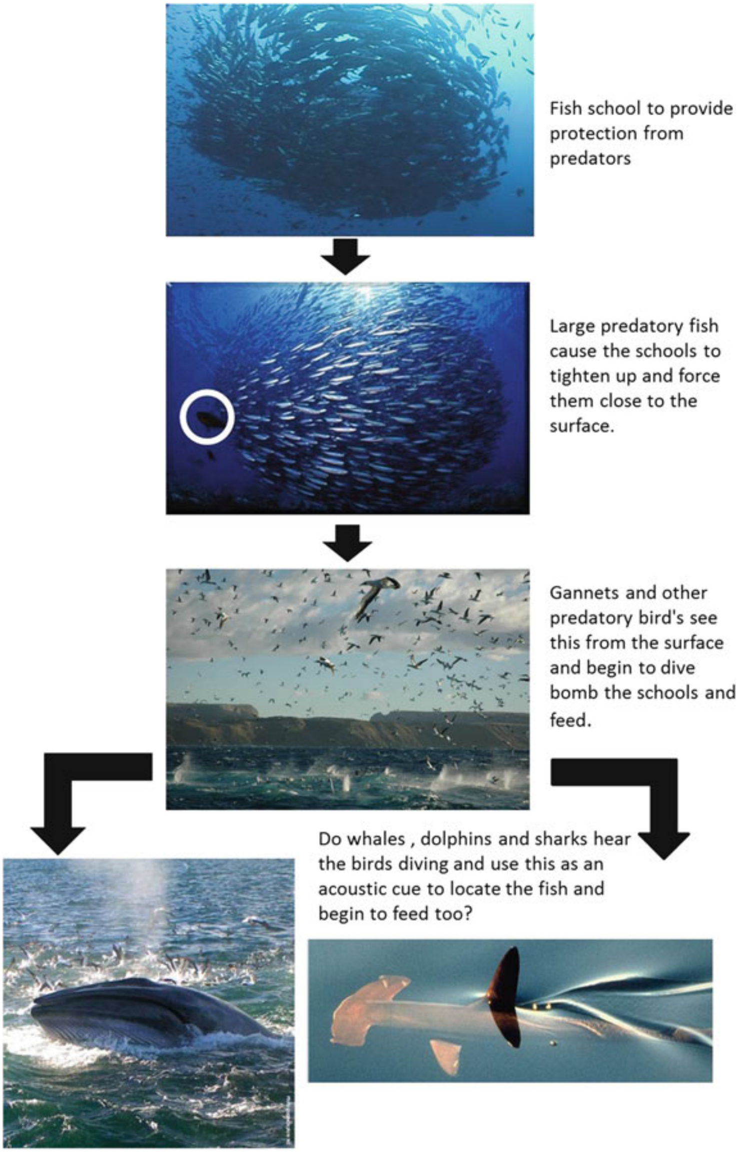
and other invertebrates respond to reef sound (Tolimieri et al. 2000). Since then, our group and others have further explored the behavior of marine animal larvae to sound (Montgomery et al. 2006), the nature of sound production on the reef (Radford et al. 2008), and reef sound transmission in shallow water (Radford et al. 2011b) and have begun to characterize the auditory ability of these larval animals (Wright et al. 2011). New evidence shows that older reef- and non-reef-associated fish, juvenile and adult, use ambient sound to relocate to different habitats (Radford et al. 2011a). Therefore, ambient underwater sound appears to be a widespread orientation cue used by a wide range of ocean fauna. These developments parallel the emerging field of "soundscape ecology" in terrestrial systems (Pijanowski 2011).

The potential also exists that "acoustic ecology" is a significant component of resource competition in the pelagic zone (the upper water column where many fish, sharks, and marine mammals forage). We hypothesize that in addition to stochastic search methods (Sims et al. 2008), acoustic ecology may provide a key channel for resource localization and hence competition between top pelagic predators (Fig. 110.1). The ocean pelagic zone accounts for almost half the planet's photosynthesis and supports rich marine food webs, globally important fisheries, and marine mammal and seabird populations. Resource patchiness and animal aggregation are fundamental features of the ocean pelagic zone (Ritz et al. 2011). Survival of the higher trophic level predators depends on finding appropriate patches of prey. The competition dynamic between individuals and species to find those patches puts pressure on the evolution of effective resource search behavior. Above the ocean surface, recent discoveries have shown that in addition to stochastic search, seabirds use a combination of olfactory and visual cues while foraging at sea (Nevitt et al. 2008). Below the ocean surface, olfactory and visual cues are limited, leading us to postulate the use of acoustic sensory ecology as a key component of resource competition in the pelagic zone.

2 Methods

The preliminary study location was undertaken in the Hauraki Gulf, New Zealand (36.3500° S, 175.0333° E). Transects were conducted up and down the Hauraki Gulf using the Leigh Marine Laboratory's research vessel Hawere. Once a school of fish was observed, we deployed an omnidirectional wideband hydrophone (HTI-96-MIN, High Tech, Inc., Long Beach, MS) to record the activity. The hydrophone had a flat-frequency response and was connected to an Edirol R-09 recording at 48 kHz, 16 bit, and the files were saved as WAV files to a secure digital (SD) card. During the deployments, the species of schooling fish were noted, and observations were made of bird activity and the timing of when marine mammals and other large pelagic predators turned up. In addition, ship traffic and other anthropogenic activity were noted.

The recording system was calibrated by taking a series of recordings of a pure-tone 1,000-Hz sine wave (root-mean-square [rms] 100 mV, 1, and 2 V) produced by a signal generator, and the voltage (V_{rms}) of the tone recording was measured and



Fish school to provide protection from predators

Large predatory fish cause the schools to tighten up and force them close to the surface.

Gannets and other predatory bird's see this from the surface and begin to dive bomb the schools and feed.

Do whales , dolphins and sharks hear the birds diving and use this as an acoustic cue to locate the fish and begin to feed too?

Fig. 101.1 Flow diagram outlining the series of events that make up the possibility that sound produced by food patches may provide a competitive foraging advantage for large marine pelagic predators

compared with the hydrophone sensitivity data. The recordings were then calibrated to decibels re 1 $\mu Pa^2/Hz$ based on the original manufacturer's calibration of the hydrophone, which had a sensitivity of -164.3 dB re 1 $V_{peak}/\mu Pa$.

Sound recordings were analyzed using MATLAB scripts specifically written for these data.

3 Results

The spectral composition of the food patches differed from that of the control and also depending on the animals present during these feeding events (Fig. 110.2a). For example, schooling trevally without any predators present produced a distinct rise

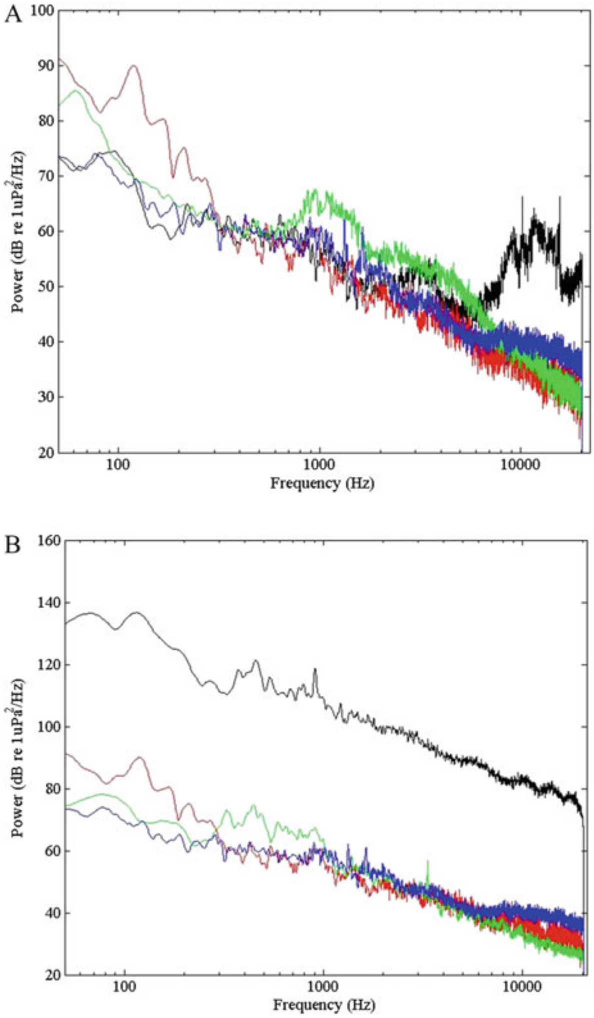


Fig. 110.2 Spectra of recorded sounds from the Hauraki Gulf. (**a**) Spectrum showing three different food patch scenarios, i.e., sound recordings with different animals present. *Blue line*, ambient background sound; *red line*, gannets diving into a school of fish; *green line*, school of trevally feeding on the surface; *black line*, dolphins feeding on a food patch of pilchards (no bird diving). (**b**) Spectrum showing how anthropogenic noise has the ability to mask the important acoustic signals produced by diving gannets. *Black line*, recording of a commercial cargo ship 100 m away; *green line*, similar ship ~20 km away

above ambient background sound in the frequency band of 600–1,500 Hz. Diving gannets with no large predators present feeding on a school of juvenile kahawai had a distinct spectral signature above background sound at frequencies between 50 and 200 Hz. Dolphin whistles while feeding on a school of juvenile kahawai with no diving birds typically increase the spectrum at much higher frequencies (20–30 kHz).

The proximity of an anthropogenic noise source, in this case a ship approaching to within 100 m, completely drowns out the sound produced by food patches. The ship peaks in intensity (120–140 dB re 1 μPa^2/Hz) at the low frequencies (50–200 Hz), which is where the gannet diving sound is prominent (Fig. 110.2b). In contrast, a similar sized vessel ~15 km away does not mask the important low-frequency sound signature of gannets diving.

4 Discussion

These preliminary results show some potential for acoustic ecology to be a component of resource competition in the marine environment. Acoustics may provide a usable channel for identifying and finding food aggregations. Feeding trevally, diving gannets, and feeding dolphins all produce distinctive acoustic signatures that could potentially be detected by a range of pelagic predators. The results also show that anthropogenic noise in the form of shipping activity has the ability to mask these acoustic signals.

The low-frequency noise produced by the diving gannets is well within the hearing range of sharks (Casper and Mann 2006), large pelagic fish (e.g., tuna; Song et al. 2006), and dolphins and whales (Yamato et al. 2012). Understanding the distance from which these animals can detect these sources is critical for understanding the competitive foraging advantage that these types of acoustic cues could provide. The distance is going to depend on the source level of the food patch, the hearing ability of the animal, and any potential competing anthropogenic sources that could mask the acoustic cues.

In conclusion, food aggregations produce identifiable sound signatures that depend on the animals involved and have the potential to be used for passive acoustic orientation. In particular, the sound of diving gannets highlights the potential for acoustic ecology to play a role in resource competition in the pelagic zone, linking foraging patterns above and below the waves. If passive acoustic orientation turns out to be important in pelagic foraging, it will provide an additional dimension to the potential use of remote acoustic sensing as a means for monitoring biologically important aspects of pelagic ecosystems.

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Chapter 111
Beyond a Simple Effect: Variable and Changing Responses to Anthropogenic Noise

Andrew N. Radford, Julia Purser, Rick Bruintjes, Irene K. Voellmy, Kirsty A. Everley, Matthew A. Wale, Sophie Holles, and Stephen D. Simpson

Abstract A growing number of experimental studies have demonstrated that exposure to anthropogenic noise can affect the behavior and physiology of a variety of aquatic organisms. However, work in other fields suggests that responses are likely to differ between species, individuals, and situations and across time. We suggest that issues such as interspecific and intrapopulation variation, context dependency, repeated exposure and prior experience, and recovery and compensation need to be considered if we are to gain a full understanding of the impacts of this global pollutant.

Keywords Condition dependency • Context dependency • Interspecific variation • Repeated exposure • Recovery

1 Introduction

Human activities such as urban development, the construction and exploitation of natural resources, and transportation have increased around the globe in the last century, changing the acoustic environment both on land and underwater (Jasny 1999; McDonald et al. 2006; Watts et al. 2007; Barber et al. 2009). In addition to the unprecedented modification of the natural soundscape, the nature of the sound generated by human activities is often very different from that arising from natural sources; anthropogenic noises may differ from abiotic or biotic sounds in such acoustic characteristics as constancy, rise time, duty cycle, and

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impulsiveness (Hildebrand 2009; Popper and Hastings 2009). Consequently, anthropogenic noise presents a very real, and often novel, challenge to animals and is now recognized as a pollutant of international concern (e.g., inclusion in the US National Environment Policy Act and the European Commission Marine Strategy Framework Directive and as a permanent item on the agenda of the International Maritime Organization's Marine Environmental Protection Committee).

In recent years, anthropogenic noise has been demonstrated to affect a variety of taxonomic groups across a range of scales, from the physiology and behavior of individuals to changes at the population and community level (see Tyack 2008; Barber et al. 2009; Popper and Hastings 2009; Slabbekoorn et al. 2010; Kight and Swaddle 2011 for reviews). Experimental studies on aquatic organisms have indicated that mammals, fishes, and invertebrates are all vulnerable. For instance, noise causes alterations in the vocal signaling, movement patterns, foraging behavior, and hearing thresholds of marine mammals (e.g., Bejder et al. 2006; Mooney et al. 2009; Di Iorio and Clark 2010; Tyack et al. 2011). In fishes, movement, settlement, foraging, social interactions, and antipredator behavior are all influenced by anthropogenic noise (e.g., Purser and Radford 2011; Bruintjes and Radford 2013; Holles et al. 2013; see Chapters 32 by Everley et al. and 129 by Simpson et al.), which has also been shown to cause stress, temporary threshold shifts, and injury (e.g., Smith et al. 2004; Wysocki et al. 2006; Halvorsen et al. 2012). Marine invertebrates, which use sound for a variety of reasons (e.g., Simpson et al. 2011; Vermeij et al. 2010), are also impacted because anthropogenic noise has both physiological and behavioral consequences (e.g., Wale et al. 2013a, b).

2 Beyond a Simple Effect

Understandably for an emerging research field (the majority of studies have been published in the last 3 years; reviewed in Radford et al. 2012; Morley et al. 2014), the main question considered in experimental studies to date has been the straightforward, yet important, "Does anthropogenic noise have an impact?" We argue that attention also needs to focus on additional questions relating to variable and changing responses to noise, and we outline some examples below.

2.1 Interspecific Differences

It is likely that there will be stable interspecific differences in susceptibility and responses to elevated noise levels depending on variation in, for example, hearing ability (Fay et al. 2008) and mechanisms of physiological stress response (Hofer and East 1998). Direct comparisons of species in response to the same noise source in the same contexts are rare. However, Halvorsen et al. (2012) recently showed variation in the level of injury caused in different fish species by exposure to the same pile-driving stimulus. Voellmy (2013) has also demonstrated that the foraging and antipredator behavior of three-spined sticklebacks (*Gasterosteus aculeatus*) and European minnows (*Phoxinus phoxinus*) is affected differently by the same noise playbacks. In sympatry, and particularly if there is an overlap in ecological niches, such differences may affect the relative success of each species under scenarios of disturbance and so potentially may affect community composition and structure. These effects could arise through alterations in the interactions between, for example, competitors, predators and prey, and plants and pollinators (see Francis et al. 2009, 2012).

2.2 Intrapopulation Variation

It is clear from other research fields that factors such as sex, dominance status, age, size, and condition may all influence how members of the same population are affected by a given stimulus, including environmental change arising from human activities (Kiffney and Clements 1996; Huntingford et al. 2006; Xu et al. 2010). Although empirical work on the impacts of anthropogenic noise has tended to focus on the overall response of cohorts of individuals, studies are beginning to consider potential intrapopulation differences in response. For instance, Wale et al. (2013a) found that heavier shore crabs (*Carcinus maenas*) consume a disproportionately larger amount of oxygen than smaller individuals when exposed to playback of ship noise. Bruintjes and Radford (2013) discovered that dominant male and female individuals of the cooperatively breeding cichlid fish species *Neolamprogus pulcher* exhibit different behavioral responses to the same playback of boat noise. More recently, Purser et al. (in preparation) have shown that European eels (*Anguilla anguilla*) in poorer body condition (relative weight) suffer more detrimental physiological and behavioral consequences than individuals in better condition. Consistent interindividual differences in response could have impacts on population dynamics and for harvests of commercially important species.

2.3 Context-Dependent Responses

The response of an animal can be dependent on its current situation (e.g., Bell et al. 2009, 2010), with increasing evidence that context can influence the harmful effects of human activities on animal welfare (see Huntingford et al. 2006 and references therein). Recent work by Bruintjes and Radford (2013) showcases that the impact of anthropogenic noise can be context dependent; playback of boat noise resulted in a reduction in antipredator defense by *Neolamprogus pulcher* group members if no eggs were present in a nest but not if eggs were present. Moreover, social interactions between dominants and subordinates were affected differently by the same noise playbacks depending on whether group members were engaged in defense behavior or nest digging. The implication is that responses to anthropogenic noise are not fixed but rather show some element of flexibility, which may or may not be under the control of the individual.

2.4 Repeated Exposure and Prior Experience

Responses to pollutants may change across time (Piola and Johnston 2009; Whitehead et al. 2010) as a result of such processes as habituation, tolerance, and sensitization (Bejder et al. 2009). Although noise-related experiments have, from an understandable logistical perspective, often involved a single presentation of the relevant stimulus, organisms in most natural situations are likely to experience chronic or repeated noise exposure. Exploring how responses can change and are dependent on prior experience is thus important (Simpson et al. 2010; see Chapter 149 by Voellmy et al.). Wale et al. (2013a) showed that although shore crabs repeatedly exposed to ambient-noise playback increased their oxygen consumption (perhaps due to handling stress), those individuals repeatedly exposed to playback of ship noise did not exhibit a similar change. It is possible that they had already shown a maximum response on a first exposure to ship-noise playback, but they might also have become habituated or tolerant over time. Voellmy (2013) has also recently demonstrated, by manipulating holding-tank noise conditions, that prior acoustic experience can influence responses of fish to experimental playbacks, whereas Nedelec et al. (2014; in preparation) have found that repeated exposure to boat-noise playback can affect subsequent behavioral and physiological responses in the early life stages of both fish and marine invertebrates.

2.5 Recovery and Compensation

Many anthropogenic noise events are transient in nature (Hildebrand 2009; Popper and Hastings 2009), and short-term impacts of noise may not necessarily translate into long-term consequences (see Bejder et al. 2006). Although it is clear that behavior and physiology can be detrimentally impacted during the period of elevated noise (see Section 1), the effects on survival and reproductive success will be dependent on whether, and how quickly, the affected individuals recover to baseline performance levels and if they can compensate. Bruintjes et al. (in preparation) have recently found that the detrimental effects of ship-noise playback on European eel antipredator behavior and respiratory rate are not sustained when the noise ceases. Species will differ in their ability to recover and compensate (Voellmy 2013), and compensation itself may carry a variety of inherent costs (see Purser and

Radford 2011). Thus, studies are needed that look at longer time frames and consider postexposure periods as well as when the noise itself is apparent.

3 Conclusions

The human population is projected to increase by 2.3 billion between 2011 and 2050 (United Nations 2011) and thus noise pollution is not just a pressing issue but one of ever-increasing concern. It is now well established that anthropogenic noise does indeed impact a wide range of animals. As the research field moves forward, we advocate the exploration of a wider range of questions such that we can understand more fully the range of effects of this global pollutant and thus optimize strategies to mitigate impacts to both aquatic and terrestrial ecosystems.

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Chapter 112

Underwater Sound Propagation from Marine Pile Driving

James A. Reyff

Abstract Pile driving occurs in a variety of nearshore environments that typically have very shallow-water depths. The propagation of pile-driving sound in water is complex, where sound is directly radiated from the pile as well as through the ground substrate. Piles driven in the ground near water bodies can produce considerable underwater sound energy. This paper presents examples of sound propagation through shallow-water environments. Some of these examples illustrate the substantial variation in sound amplitude over time that can be critical to understand when computing an acoustic-based safety zone for aquatic species.

Keywords Pile driving • Propagation • Peak • Root-mean-square • Sound exposure level

1 Introduction

Impact pile driving occurs in a variety of nearshore environments that typically have very shallow-water depths. The propagation of pile-driving sound into water is complex, where sound is directly radiated from the pile as well as through the ground substrate. Pile driving in aquatic environments is typically restricted when there is the presence of protected fish species or marine mammals.

Resource agencies are typically charged with assessing the potential harmful effects to fish and marine mammals. For the adverse acoustical effects from pile driving, these assessments rely on the prediction of sound in terms of received peak pressures, root-mean-square (rms) sound pressure levels, and sound exposure levels (SELs). Numerous thresholds have been developed to assess these impacts. An example of these thresholds is shown for projects along the west coast of the United States in Table 112.1 (Fisheries Hydroacoustic Working Group (FHWG) 2008; National Oceanic and Atmospheric Administration (NOAA) 2012).

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Table 112.1 Thresholds used to evaluate acoustical effects to aquatic species

Species of concern	Acoustical descriptor	Threshold
Fish	Peak	206 dB
	SEL (accumulated)	187 dB for fish size of 2 g or greater
		183 dB for fish size below 2 g
Pinnipeds	rms (pulse)	190 dB for injury (pinnipeds)
		180 dB for injury (cetaceans)
		160 dB for behavior

Peak and root-mean-square (*rms*) sound levels are in decibels re 1 μPa. Sound exposure level (*SEL*) is in decibels re 1 $\mu Pa^2 \cdot s$

Peak and rms thresholds are based on received sound levels, whereas SEL thresholds are associated with the dose of sound received over an entire workday. Therefore, the received peak and rms levels are a function of the source level and propagation rate, whereas the received SEL level also includes the other variable of time. In open water, the distance to peak pressure thresholds can be on the order of tens of meters, the distance to accumulated SEL thresholds is over 100 m, and behavioral disturbance rms levels for marine mammals can be over 1,000 m. As a result, the area of acoustical effect can be quite large and difficult to predict or assess. The prediction of these areas of effect requires that one knows the source or near-source sound levels and the sound-propagation rate. Near-source levels for various pile-driving activities are fairly well documented (ICF Jones and Stokes and Illingworth and Rodkin 2009). A simple propagation model is typically used to predict sound levels and the size of areas of effect. For example, NOAA Fisheries uses the following equation to estimate this transmission loss (TL) or the propagation rate to threshold levels (Stadler and Woodbury 2009).

$$\mathrm{TL} = C \ \log_{10}\left(\frac{R_1}{R_0}\right)$$

where TL is in decibels, C is the TL constant, R_0 is the distance from the pile to the known sound level, and R_1 is the distance from the pile to the threshold level or level of interest. The TL is the difference in the sound level from the known sound level at distance R_0 and the predicted sound level at distance R_1.

Most pile driving occurs in relatively shallow water (tens of meters deep or less), with a variety of substrate types and structures (e.g., piers, barges, ships). Thus, the rate of propagation (or TL) can vary widely from site to site, requiring site-specific information to accurately estimate (ICF Jones and Stokes and Illingworth and Rodkin 2009). However, in most cases, site-specific data are not available, and the National Marine Fisheries Service, NOAA, assumes a TL constant of 15 (a 15 $\log_{10}$ propagation function).

A review of pile-driving near-source levels indicates that peak levels are 10–15 dB greater than rms levels and ~25 dB greater than SEL levels (ICF Jones and Stokes and Illingworth and Rodkin 2009). For impact pile driving with peak sound levels of 200 dB or greater, this could equate to an impact ranging out to 1,000 m, assuming a 15 $\log_{10}$ function to compute sound propagation. Slight changes in the propagation rate result in relatively large distance changes. For example, behavior impacts to marine mammals would range from 582 m with a 17 $\log_{10}$ drop-off rate to 1,390 m for a 14 $\log_{10}$ drop-off rate, assuming the 200-dB peak level at 10 m. The range of the potential impact area for marine mammals in this case would be over 800 m.

This paper presents examples of sound propagation through shallow-water environments for three different impact pile-driving projects. In addition, the change in the sound characteristics over time and distance (e.g., amplitude and frequency content) are presented for these examples. Some of these examples illustrate the substantial variation in sound amplitude over time that can be critical to understand when computing acoustic-based safety zone for aquatic species.

2 Examples of Measured Levels

2.1 Benicia–Martinez Bridge Construction

Detailed underwater sound measurements were conducted during driving of the large 2.7-m-diameter steel shell piles used to construct the new Benicia–Martinez Bridge. These piles were driven in water depths of ~20 m using a hydraulic Menck 500 hammer that delivered 580 kJ of energy to drive the pile. For unattenuated conditions, sound measurements were made at positions from 5 to 1,000 m away from the pile (Reyff et al. 2002). Sound levels measured continuously during the driving of a pile indicated little change in amplitude over time. The sound pressure levels, in terms of peak, rms, and SEL, decreased fairly uniformly over distance (see Fig. 112.1).

Unattenuated pile-driving sound levels were found to uniformly decrease at a rate described by using a 16–17 $\log_{10}$ function. An air bubble curtain system typically provided 10–15 dB or greater sound attenuation. Table 112.2 shows the distances to the various thresholds using predictive and measure sound-propagation rates. The effect of the slightly different propagation rates has a small effect for assessing peak and rms injury thresholds. However, the effect is quite large when assessing the accumulated SEL effects on fish. The effect is most pronounced under unattenuated conditions; however, most pile-driving operations are required to include attenuation. The variation in the impact zones using the 15 $\log_{10}$ rate and in the measured rate is still considerable. The measured rate indicates an adverse effect area that is ~56% smaller compared with the area computed using a 15 $\log_{10}$ rate.

2.2 Navy-Kitsap Bangor Wharf Construction

In 2011, the US Navy conducted a test pile program at Naval Base Kitsap, Bangor, WA (Illingworth and Rodkin 2012). The project was conducted to support design of a new explosives handling wharf. The project included the impact driving of 0.6- to 1.2-m-diameter steel piles in relatively deep water (deeper than 25 m). The project is located at the Hood Canal. Water depth in the Hood Canal where sound

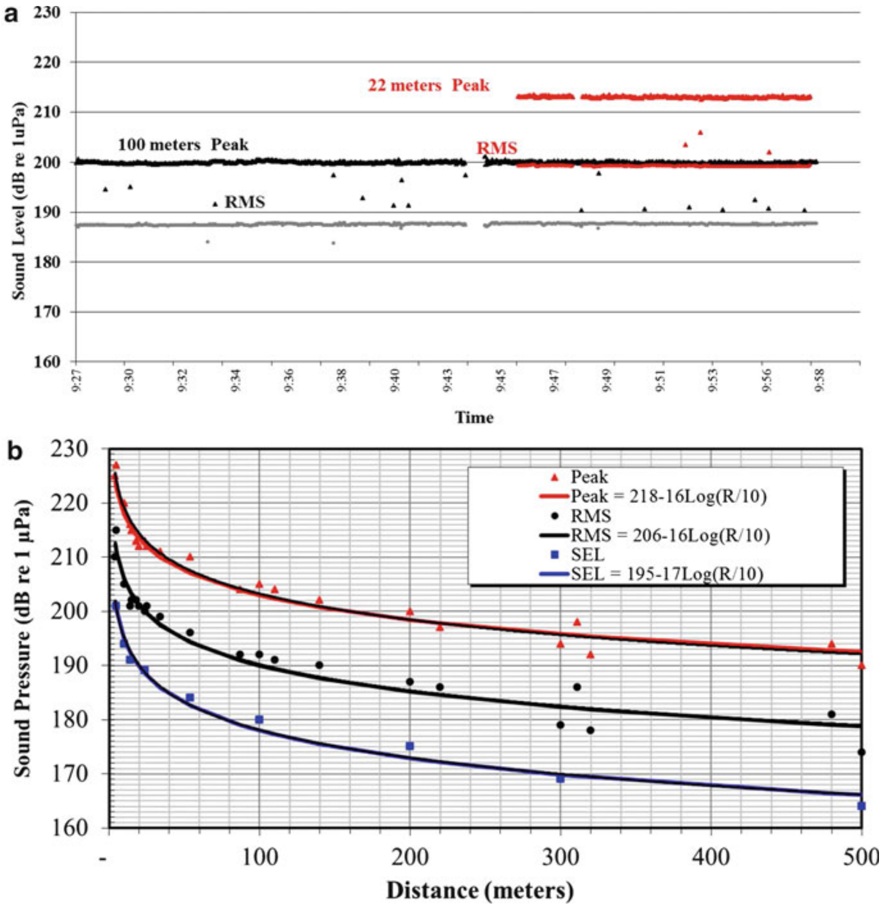

Fig. 112.1 Measured sound pressure levels plotted over time (**a**) and distance (**b**). *SEL* sound exposure level, *rms* root-mean-square

Table 112.2 Effect of different propagation rates used to evaluate acoustical effects to aquatic species at the Benicia–Martinez Bridge

Propagation rate	Peak threshold for fish, 206 dB	rms threshold for injury to pinnipeds, 190 dB	Accumulated SEL for fish, 187 dB assuming 1000 pile strikes
15 $\log_{10}$ rate	Unattenuated = 63 m	Unattenuated = 117 m	Unattenuated = 3415 m
	Attenuated = <10 m	Attenuated = 12 m	Attenuated = 341 m
Measured rate: 16 $\log_{10}$ for peak and rms and 17 $\log_{10}$ for SEL	Unattenuated = 51 m	Unattenuated = 100 m	Unattenuated = 1719 m
	Attenuated = <10 m	Attenuated = 12 m	Attenuated = 225 m

measurements were made exceeded 100 m. The Navy conducted an extensive acoustical-monitoring program is support of biological monitoring that included both near and distant measurements. Measurements conducted for impact pile driving of 1.2-m-diameter piles at distances from 10 to 1,500 m indicated a propagation rate of 13 $\log_{10}$ when no attenuation system was used. When the attenuation system was used, the rate was more variable, ranging from ~11 $\log_{10}$ to a 14 $\log_{10}$ rate. The decreased propagation rate with the attenuation system operating is thought to be associated with the greater effectiveness of the system to reduce sound levels closer to the pile. The Navy predicted the effects to biological resources using near-source data obtained from various literature and applied the 15 $\log_{10}$ propagation rate. As a result of the lower propagation rate, the size of behavioral-based areas of effect for marine mammals and fish exceeded the predicted sizes by 100 to almost 200%. However, most of these areas of effect were bounded by land.

2.3 Geyserville Russian River Bridge

The Geyserville Russian River Bridge project involved acoustic monitoring while permanent steel pier piles were driven using a Del Mag D100-13 hammer (ICF Jones and Stokes and Illingworth and Rodkin 2009). The hammer has a maximum obtainable energy of ~336 kJ. The river is very shallow, with a main channel depth of ~2 m. This example is based on measurements made 10–75 m from the pile that was driven in the main part of the channel. The piles were driven to a depth at which there was sufficient skin friction to support the bridge (~45 m).

Figure 112.2a shows the measured peak sound pressures at each position from 10 to 75 m from the pile plotted over time during the entire driving event. In this example, we divided the driving event into three periods: beginning, middle, and end. Impacts driving involved the most hammer energy near the end when the pile tip penetrated more than 30 m into the substrate. Sound levels varied at each position over time. For example, sound levels at the closest position were highest during the beginning of the drive and lowest near the end. A similar trend occurred at the 20-m position, where sound levels were naturally lower than the 10-m position for most of the driving period until near the end (Fig. 112.2a, Part 3). Relatively consistent levels occurred at 40 and 75 m. It is noted that levels measured at 40 m were higher than levels measured at 10 and 20 m near the end of the driving event.

The sound-propagation rate varied because sound levels varied considerably at the near-source position, whereas there was less variation at the more distant positions. Figure 112.2b shows the peak sound level plotted by distance for each of the three driving periods. The 15 $\log_{10}$ propagation rate is also plotted using the 10-m near-source level. What is important to note is that the near-source levels and the propagation rate changed considerably over the driving of this pile. It is hypothesized that as the skin friction increased on the pile, the sound emanating from the pile was dampened, whereas the sound from within the substrate remained the same or increased. When pile driving first began, the propagation rate from 10 to 45 m was similar to a 15 $\log_{10}$ rate. During the second and third portions of the driving event, sound levels

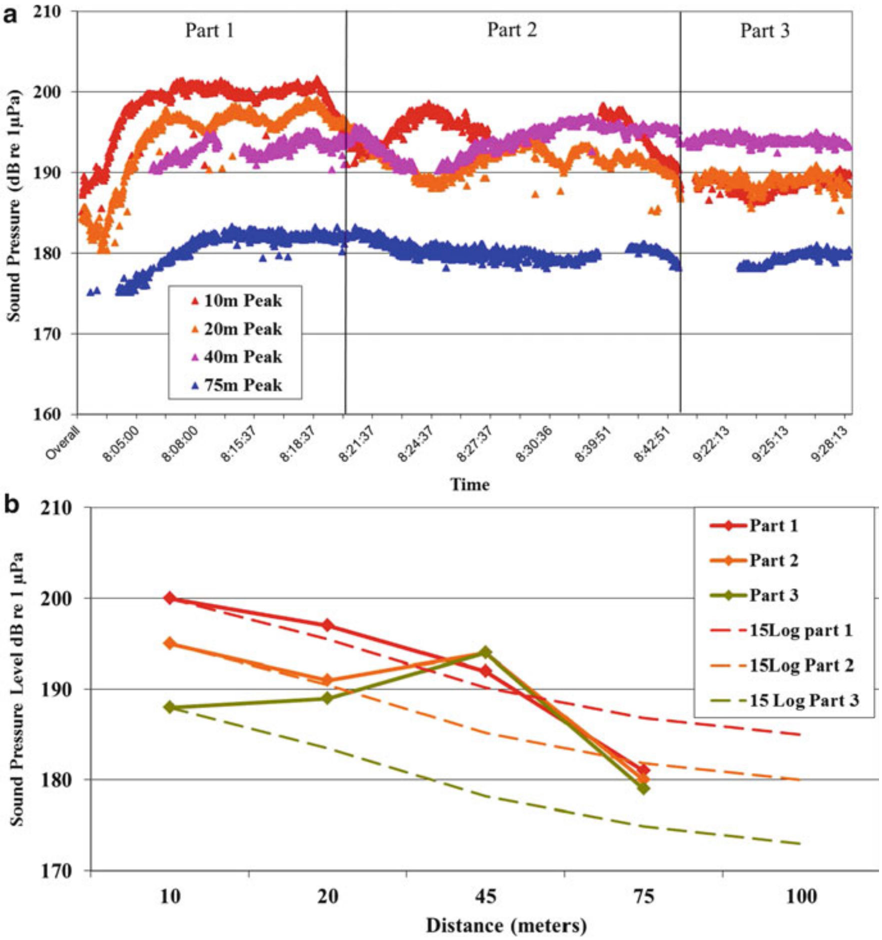

Fig. 112.2 Measured sound pressure levels plotted over time (**a**) and distance (**b**). Three separate time periods during the pile-driving event are depicted

near the pile decreased by 5–12 dB, resulting in a nearly flat sound-propagation rate. However, the rate from 45 to 75 m remained constant for all portions of the pile-driving event, which was similar to a 30 $\log_{10}$ propagation rate. Use of the 15 $\log_{10}$ propagation rate would have provided fairly accurate predictions out to 45 m for only the first part of the driving event when near-source levels were loudest.

3 Conclusions

The examples presented in this paper illustrate the complexity of predicting sound levels at various thresholds using simple or measured sound-propagation rates. In the relatively deep-water cases presented, measured sound levels are fairly consistent over time and a relatively uniform sound-propagation rate is obtained. These rates can be slightly above or below the 15 $\log_{10}$ rate suggested by NOAA. In very shallow water (e.g., river bodies), the sound level can be highly variable and appears to be affected just as much by sound generated in the substrates rather than radiating off the pile itself. The propagation rate for very shallow water can range from the typical 15 $\log_{10}$ rate to a nearly flat rate for close-in positions (e.g., within 50 m) but then falls off abruptly at rates well in excess of 15 $\log_{10}$ at greater distances. Predicting this effect would require a detailed understanding of the environment that the sound would radiate through over the course of the pile-driving event. In most shallow-water environments, the 15 $\log_{10}$ propagation rate should predict sound levels at distances of over 50 m. However, caution should be used when water depths are deep, i.e., over 25 m, where the sound-propagation rate can be $<15 \log_{10}$.

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Chapter 113
Effects of Sound on the Behavior of Wild, Unrestrained Fish Schools

Louise Roberts, Samuel Cheesman, and Anthony D. Hawkins

Abstract To assess and manage the impact of man-made sounds on fish, we need information on how behavior is affected. Here, wild unrestrained pelagic fish schools were observed under quiet conditions using sonar. Fish were exposed to synthetic piling sounds at different levels using custom-built sound projectors, and behavioral changes were examined. In some cases, the depth of schools changed after noise playback; full dispersal of schools was also evident. The methods we developed for examining the behavior of unrestrained fish to sound exposure have proved successful and may allow further testing of the relationship between responsiveness and sound level.

Keywords Underwater sound • Sonar • Pelagic fish • Behavior • Mackerel • Playback

1 Introduction

A number of sound playback experiments have been undertaken in recent years, but the majority of these have been undertaken on captive fish. Laboratory studies have shown a behavioral response by fish to sound stimuli (Blaxter et al. 1981; Kastelein et al. 2007, 2008); however, the acoustic conditions within small tanks are not

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directly comparable to the natural environment (Griffin 1950; Parvulescu 1964), making the results of such studies difficult to interpret.

To address this problem, a number of field-based studies have been undertaken (e.g., Engås et al. 1995; Boeger et al. 2006; Thomsen et al. 2012) but have used large cages or netting pens. Fish tend to behave differently when enclosed than when they are free and unrestricted (Benhaïm et al. 2012), especially if they have been bred in captivity or damaged during capture and handling (Balaa and Blouin-Demers 2011), putting the results of these studies into question.

With this in mind, to fully evaluate the responses of wild fish to man-made sounds, experiments with free-swimming fish in their natural habitat with a passive observation technique are preferred. The logistics of such experiments are not simple because of the difficulties of monitoring unrestrained fish without influencing their behavior and the issues of accurately reproducing sounds on demand. However, the study outlined here is a successful example of such a field experiment. The methods developed here may be the first step in investigating the responsiveness of free-living schools of fish to various sounds at different levels.

2 Materials and Methods

Experiments were undertaken at Lough Hyne, County Cork, Ireland (51°30′ N, 9°18′ W). This site has been a marine nature reserve since 1981 and has a low level of boat activity. Human influence is minimal, providing quiet conditions for sound experiments. Previous studies have shown large numbers of *Sprattus sprattus* (sprat) in the lough, appearing as large schools during the day when the fish are preyed on by *Scomber scombrus* (mackerel). These schools break up at night, and the individual fish disperse over a wide area (Hawkins et al. 2012).

The experiments were undertaken in two trips, 20–27 October 2012 and 17–23 March 2013, with four previous trips to develop the experimental setup and methodology and to map the locations of fish schools.

2.1 Observations of Fish Behavior

A rigid inflatable boat (RIB) with an outboard motor and a small rowing boat were tethered together and allowed to drift without power for the experiments. A Humminbird 998c SI sonar was mounted on a wooden beam and suspended from the side of the rowing boat at a depth of 0.5 m. The transducer produced a downward beam (20° width) at 200 kHz and side scan beams at 800 kHz, both operating well above the hearing range of the species investigated. Sonar recordings were saved onto a secure digital (SD) memory card together with GPS data and were later viewed with Humviewer software.

2.2 Sound Playback and Monitoring

A custom-made sound projector array (Subacoustech Ltd.) was used to play back clips of synthetic pile-driving sound. The system consisted of four underwater projectors specifically made to produce low-frequency sounds. This unit was suspended from the RIB as far away from the sonar beam as possible to avoid it appearing as a strong target on the sonar system. An InPhase IPX2,400 car amplifier (2,400 W) powered by a car battery was connected to the speakers, with the input signal played from a Tascam model DR05 recorder or an IBM ThinkPad laptop computer.

The 20-s-long synthetic sound in the playback experiments consisted of ten sharp-onset low-frequency pulses intended to mimic the signal from a pile driver. Each "strike" was 2 s apart and was constructed from white noise of 50–600 Hz, with the most power at 200 Hz to mimic the spectral characteristics of piling. To avoid pseudoreplication, six versions of the sound were used, each created with the same characteristics (i.e., onset time and filtered frequency ranges) but with a different white noise used in each case. Six levels were played, in increments of 5 dB below the maximum volume. The order of the versions and levels of the signatures were fully randomized, with "silences" interspersed to check that the equipment itself did not have an influence on the fish.

A series of calibration measurements was taken to enable calculation of the received levels at the top of the acoustic targets. The calibrations were made using a Reson TC4014 hydrophone with a sensitivity of −186 dB re 1 V for a sound pressure of 1 μPa, with a frequency range from 0.1 Hz to 400 kHz. A custom-made amplifier (Subacoustech Ltd.) was used to amplify the signal by between 0 and 40 dB and a National Instruments type 606E data-acquisition device (sampling rate of 350 kHz) was used to digitize the signal before storage on a laptop. Sound-level measurements were taken each day at a number of depths from 4 to 19 m, enabling the levels received by the fish to be estimated.

2.3 Experimental Procedure

The two boats were allowed to drift, without power, until the sonar system displayed characteristic acoustic targets from fish. Sound playback then commenced, and the resulting responses from the targets were recorded on the Humminbird sonar. The coupled boats drifted across the lough under the action of the wind and tide, with sound playback being undertaken when targets were encountered. Often, multiple schools were encountered on each track, but suitable gaps (5–10 min while the boat continuously drifted) were left between presentations to avoid exposing the same school on multiple occasions. Recordings from the Humminbird were made continuously, with a new recording track for each location within the lough. The positions and timing of each sound playback were noted, recorded using the waypoint facility on the Humminbird, and subsequently displayed on the sonar trace.

Playback of blank sound files interspersed between full experimental sound presentations was carried out at random intervals as a control.

Playback experiments were typically undertaken on schools at <25 m depth. In the October experiments, fish schools were only found at depths shallower than 30 m because of the presence of a strong thermocline below which oxygen levels were greatly reduced. In the March experiments, the thermocline was absent. Sampling was generally undertaken under calm sea conditions (Beaufort Sea state two and below) to ensure that the vessel drifted at a suitable slow speed (average speed of 0.16 m/s^2). Sampling of the acoustic targets detected on the Humminbird was undertaken by rod-and-line fishing and plankton net tows.

2.4 Data Analysis

Data were pooled together for the purposes of analysis. Echograms were viewed in Humviewer (version 67) software, with the precise times of playback marked using the waypoint tool. “False” playbacks were randomly added to display some schools that were not exposed to sound playback so that normal behavior could be observed. Echograms were scored as a response (1) or no response (0) by two experienced observers, and the binary data were then analyzed in SPSS (version 19) to investigate whether the sound level had an effect on the response. For analysis, the targets were grouped into categories according to density, size, and overall appearance.

3 Results

A total of 236 targets (aggregations and individual targets) were exposed to sound playback at received levels ranging from 148.6 to 103.9 dB re 1 $\mu Pa^2 \cdot s$ (sound exposure level [SEL]) per strike, from 158.6 to 113.9 dB re 1 $\mu Pa^2 \cdot s$ (SEL) over the 20-s duration of a playback, or from 171.3 to 127.9 dB re 1 µPa peak to peak, with energy predominantly in the range of 50–800 Hz. The sound pressure level 5 m from the speakers was recorded as being 164–168 dB re 1 µPa (peak to peak) and 170–172 re 1 µPa (peak to peak) for October and March, respectively. Targets were recorded in a range of depths from 4 to 35 m in similar regions of the lough on both trips.

The aggregations of small targets were confirmed to be sprat and looser aggregations of larger targets as mackerel. Very small diffuse targets, seen in one region of the lough, were thought to be zooplankton as previously described by Hawkins et al. (2012).

Responses were seen to sound playback at a variety of sound levels. These responses involved density changes within aggregations, dispersal (complete cutoff and reemergence at a different depth), and depth changes. Two examples of the behavior of sprat schools in response to sound playback are shown in Figs. 113.1 and 113.2. Both of these were classed as responses. The beginning and end of the playback period are marked with a line. In addition to the downward pointing sonar

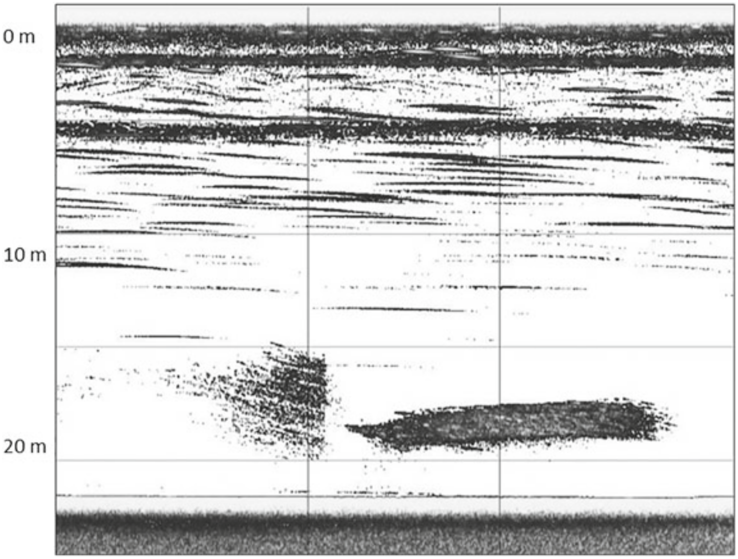

Fig. 113.1 Echogram of responses of sprat schools to sound playback on 25 October. A sprat school showed an abrupt cutoff at the beginning of the playback and reappeared a few seconds later lower in the water column and more densely packed

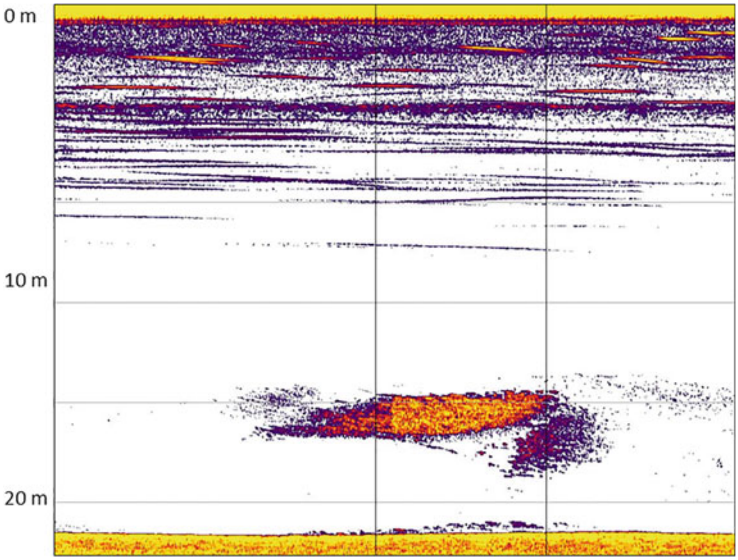

Fig. 113.2 Echogram on 24 October. The school appeared to become more dense after the onset of playback as shown by the *brightening of the color*

beam, the side scan beam also proved to be a useful additional tool to aid in the determination of the responses. The use of "silent" playbacks showed that the equipment had little effect on the targets, and "false" playbacks gave an indication of the behavior of the targets in the absence of noise.

4 Discussion

The data obtained from these experiments confirm that the responses of free-living fish to the playback of sound can readily be observed and used as a basis for determining those sound levels and sound characteristics that produce a clear-cut response. The methodology and equipment were reliable and easily reproduced. Because the boat was drifting in the water throughout the experiments, it was possible to monitor a school for long enough to play back sounds and determine the response. Concerns that a "response" may actually be a school just leaving the sonar beam can be addressed by large numbers of replicate experiments and the insertion of controls and false playbacks where no sounds are presented. The possibility that the equipment itself had an influence on the fish (for example, shadow or other visual effects) was removed.

Fish did move in and out of the beam of the sonar (and moved within the beam) on some occasions even when sounds were not presented simply as part of their normal behavior. However, by describing particular criteria for a positive response, any confusion was generally avoided. There were very few occasions when positive responses were recorded in the absence of sound playback.

The experiments were conducted in an enclosed area, under very quiet sea-noise conditions, with fish that were not being exposed to sounds from other man-made sources. Whether fish that are repeatedly exposed to a variety of man-made sounds react remains to be determined through further experiments.

The sounds produced in this study mimicked the water-borne sounds produced by a pile driver in the water column. However, it should be noted that a pile driver also produces a strong ground-borne vibration through the impact of the pile with the seabed. This vibration travels outward from the source along the seabed (via compressional, shear, and Rayleigh waves; see Chapter 53 by Hazelwood and Macey) and the energy is also passed back into the water column. The sound projector array used in this study cannot reproduce these ground-borne vibrations, which may be especially important for fish and crustaceans close to the seabed. The fish investigated here were pelagic, however, and ground-borne vibration may not be important to these species. In addition to this, the noise level in this study is roughly representative of the level 1 km from a pile driver and ground-borne vibrations at this distance may be minimal.

Sonar is commonly used to observe the behavior of fish schools and has been used in the past to investigate reactions to research vessels (see De Robertis and Handegard 2013, for a comprehensive review). There have been fewer studies involving sonar observations with playback systems, but behavioral changes such as the ones described here have been shown before. Doksæter et al. (2012) used upward-pointing sonar and found that captive *Clupea harengus* (herring) showed an increase in school density and a depth change in response to engine noise and impulsive sounds. Furthermore, Slotte et al. (2004) used sonar to observe fish schools and found that the pelagic species showed depth changes when exposed to seismic air guns. Diving of schools and the scattering of individual fish are likely to be the standard responses of pelagic fishes in reaction to a threat, such as a predator; for example, Wilson and Dill (2002) found that herring dropped in the water column increased in speed when exposed to predator (simulated odontocete) sounds.

5 Conclusions

The methods described in this study enabled the reactions of free-living unrestrained fish to be observed in response to the playback of sounds. The responses were clear, but there were indications that the type of reaction may vary depending on the received sound level, the type of fish school, and perhaps the nature of the sound stimulus. There is a clear need to describe those behavioral responses to man-made sounds that may have harmful effects on fish populations and to distinguish these responses from incidental responses that have little impact. Further experiments of this kind on free-living fish will undoubtedly yield useful results.

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Chapter 114
Sensitivity of Crustaceans to Substrate-Borne Vibration

Louise Roberts and Thomas Breithaupt

Abstract There is increasing interest in the responsiveness of crustaceans to vibrations, especially in the context of marine developments where techniques such as pile driving create strong vibrations that are readily transmitted through the seabed. Experiments were undertaken under controlled conditions to investigate the sensitivity of unconditioned crustaceans to substrate-borne vibration. The subjects were exposed to a range of frequencies and amplitudes using the staircase method of presentation to determine the thresholds of response. Behavior varied according to the strength of the stimuli and included bursts of movement and rapid bouts of movement.

Keywords Substrate vibration • Sensitivity threshold • Crustaceans • Anthropogenic noise • Vibration reception

1 Introduction

In addition to the sound pressure variations accompanying transmission of a sound, there is also a back-and-forth motion of the component particles of the medium, the particle motion. It has been conjectured that crustaceans are responsive to particle motion rather than sound pressure (Goodall 1988; Breithaupt and Tautz 1990; Budelmann 1991; Popper et al. 2001). Sound is widely produced by crustaceans (Schmitz 2002); however, the biological relevance of production is unclear and their sensitivity to signals is relatively unknown compared with that of fish.

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The particle motion component of a signal can propagate away from a source via the water column, the seabed (Nedwell et al. 2003) or a combination of both. In the seabed, this energy can be transmitted as compressional, shear, or surface waves (for example, Rayleigh waves; Aicher and Tautz 1990), with the signal changing in terms of frequency and amplitude with attenuation (see Markl 1983, for a comprehensive review of this topic). There is very little information on the ability of UK coastal crustaceans to detect these waves. For the purposes of this paper, the term vibration will refer to substrate-borne particle motion (Hill 2009).

2 Detection Mechanisms

There is evidence that detection of particle motion utilizes mechanoreceptors located in the joints, antennal flagellae, statocysts, and appendages (Tautz and Sandeman 1980; Breithaupt and Tautz 1988, 1990; Goodall 1988; Monteclaro et al. 2010). Particle motion is higher for a given sound pressure in the near field of a sound source, and it has been shown that *Nephrops norvegicus* (Norway lobster) only responds to sound stimuli <1 m away (Goodall 1988; Breithaupt and Tautz 1990).

Methods for studying sensitivity involve the isolation of particular sensory detectors, for example, the statocysts, thorax hairs, campaniform sensilla, antennules, or chelae mechanoreceptive hairs (Barth 1980; Tautz and Sandeman 1980; Breithaupt and Tautz 1988; Monteclaro et al. 2010). However, a full understanding of the sensitivity of the whole organism requires observations on the behavioral responses to vibration. For example, Goodall (1988) observed that *N. norvegicus* responded to stimuli with clear postural changes (abdominal extension and claw waving). These were clear enough to test the threshold of response to waterborne particle motion in the laboratory and the field. Heinisch and Wiese (1987) and Berghahn et al. (1995) reported clear flicking of the second antennae of *Crangon crangon* (brown shrimp) in response to vibration. Antennal movements in *Orconectes limosus* (spiny-cheek crayfish) have also been reported in response to a waterborne stimulus (Tautz 1987). Another cue utilized has been displacement of the walking legs (Breithaupt 2002).

3 Sensitivity to Vibration

Other studies have focused on the semiterrestrial fiddler crabs (*Uca* sp.) rather than marine species because they use substrate vibrations to communicate during reproductive behavior (Aicher and Tautz 1990). Thresholds of sensitivity were determined using electrophysiological techniques (Salmon and Horch 1973; Salmon et al. 1977; Aicher and Tautz 1984), behavioral observations (Salmon and Atsaides 1969) or a combination of both (Salmon 1971; Salmon et al. 1977). The sensitivity of *Homarus americanus* (American lobster) and *C. crangon* to vibrations has also been investigated (Offutt 1970; Heinisch and Wiese 1987).

3.1 Data Collation

The response thresholds of *Pagurus bernhardus* (common hermit crab) to vibration were investigated in the current study. Hermit crabs were chosen due to the clear antipredator mechanism (withdrawal) they exhibit under stressful conditions (Chan et al. 2010). Thresholds to substrate vibration were determined at several frequencies using the staircase method of threshold determination described by Cornsweet (1962).

Thresholds to vibration by other crustacean species have been summarized from the literature (Salmon and Atsaides 1969; Salmon 1971; Salmon and Horch 1973; Barth 1980; Aicher and Tautz 1984; Heinisch and Wiese 1987; Berghahn et al. 1995) and are compared with those for hermit crabs. Threshold values are given as they were originally stated and are also converted into particle acceleration, if necessary, for comparison. Care must be taken when interpreting the results of these studies because a wide range of techniques has been used. The values of sensitivity to waterborne particle motion are not provided here because this is not the focus of the paper.

3.2 Experimental Methods

Hermit crabs were kept in holding tanks at low densities (water temperature, on average, 11°–12°) in an isolated cold room under a 12:12-h light:dark regimen before the experiments. The crabs were fed a diet of mixed shellfish every 2 days and starved for 48 h before use. Experiments were carried out on individual crabs in a plastic tank (51×41 cm) with a water depth of 31 cm and a sand substrate (depth 1.5 cm). The tank sat on a custom-made base built to minimize vibrations entering the tank from the ground. Each crab was acclimatized in the experimental tank overnight before threshold determination. The experimental tank incorporated a small custom-made "arena" within which the subject could freely move during the presentations.

The subjects were presented with sine waves in the range of 5–400 Hz at each of 11 different amplitudes. A Roland R-09HR MP3 recorder connected to a car amplifier (JL Audio XD 200/2 200 W two channel) and an LDS v101 electromagnetic shaker was used to play back the signals. The shaker was mounted above the experimental tank on a separate frame from the base, with a custom-made carbon-fiber stinger rod descending vertically to the substrate.

Substrate vibrations in the vertical axis were recorded continuously with a waterproof Bruel & Kjær piezoelectric accelerometer (type 4,333, sensitivity 20.6 mV/g) connected to a battery-powered Bruel & Kjær charge amplifier type 2,635, an ADInstrument Powerlab module, and a laptop computer with Chart 5 software (version 5.5.6) installed. In later experiments, a 3-dimensional waterproof geophone (SM-7 370 Ω; IO) connected to the same ADInstrument Powerlab module was used to determine the vibrations in all three axes. Calibration measurements were taken at the end of experiments to measure the vibration inside the arena. This enabled the calculation of a correction factor for received vibrations inside the arena from the measurements taken next to the arena.

Thresholds were determined at each frequency by the staircase method (Cornsweet 1962). The threshold was estimated as the amplitude of the stimulus that the animals reacted to in 50% of the presentations, taken as an average of ten iterations. A TV camera was situated above the tank and was connected to a small LCD screen that was situated on a table away from the experimental tank. The experimenter could then sit at a distance without influencing the subjects behavior and adjust the signal accordingly.

One crab was tested per day, with the order of frequency presentation randomized. Amplitudes of each frequency were presented 2 min apart after preliminary tests indicated that reactions lasted for only a few seconds after each stimulus ended. Between frequencies, there was a gap of 20–30 min to allow the subject to recover.

4 Results

Clear behavioral changes could be seen in response to vibrations. These ranged from a full or partial retraction into the shell at the highest signal amplitudes down to a clear "sweep" of the antennular flagellum at the lowest amplitudes, with other postures in-between.

The highest sensitivity to vibration was measured at 10 Hz, with an average sensitivity value of 0.10 m/s^2 ($n = 10$) in the vertical direction. A flat response curve was obtained overall, with sensitivities ranging between 0.1 and 0.5 m/s^2, with the values at 100 and 200 Hz being slightly higher (thought to be due to a slight variation in the input signal). Background vibration levels on the vertical axis were in the region of 0.001 m/s^2. The stimulus itself was sinusoidal, with typically >85% of the energy at the desired frequency, and was strongest in the vertical axis. The highest sensitivity of 0.1 m/s^2 at 10 Hz is in the region of previously reported sensitivities to vibration; for example, Heinisch and Wiese (1987) reported a threshold of 0.81 m/s^2 for *C. crangon* . Other threshold values from the literature are shown in Table 114.1.

5 Discussion

The data presented show that the majority of the thresholds fall below 200 Hz, that is, the crustaceans examined appear to be most sensitive to low frequencies, which are likely to be within the range of biological signals (Hill 2009). Detection of low-frequency vibrations may be useful for prey location, predator detection, reproductive display, communication, and advertisement as seen in terrestrial organisms such as insects and scorpions (Hill 2009). However, evidence for these uses has only been seen in the semiterrestrial *Uca* sp. This degree of sensitivity raises the question of whether man-made vibrations, generated by pile drivers, seismic air guns or operating wind turbines, may also be detected. Unfortunately,

Table 114.1 Thresholds of highest sensitivity to vibration for a variety of crustacean species

Reference	Threshold, m/s^2	Threshold, µm	Frequency, Hz	Species	Method of determination
Aicher and Tautz (1984)	0.005		20	*Uca pugilator*	Electrophysiology
Berghahn et al. (1995)	0.4[a]		20–200	*Crangon crangon*	Behavioral
Heinisch and Wiese (1987)	0.81	0.7	170	*Crangon crangon*	Behavioral
Salmon and Atsaides (1969)	0.067[a]	0.03	400	*Uca pugilator*	Behavioral
Salmon and Horch (1973)	0.0175[a]		50	*Uca minax*	Behavioral
Salmon (1971)	0.04		30	*Uca pugilator*	Behavioral and electrophysiology
	0.06		60	*Uca rapax*	
Barth (1980)	0.0002	0.4	20–20	*Carcinus maenus*	Electrophysiology
			100–130		

Units of measurement are given as originally stated (acceleration or displacement)
[a] Units of measurement that have been converted

despite their importance for evaluating effects, few data are available on the levels of substrate vibration produced by anthropogenic activities. There have been recent attempts to measure and model vibrations such as pile driving (Hazelwood 2012; see Chapter 53 by Hazelwood and Macey), but field measurements are required before the effects of these vibrations on crustaceans can be fully understood and predicted.

In this study, the vibratory stimulus was presented using a stinger rod connected to the substrate in a tank. This may not be representative of a typical anthropogenic source of vibration, such as an impact pile driver, because the vibration may propagate through the substrate in a number of different ways. Although the tank setup is far from perfect, in light of the paucity of data on this subject, these experiments provide an important first step in investigating the effects of man-made sources of vibration on bottom-living crustaceans. Ideally, a special tank able to re-create the full range of substrate waves should be used for such experiments. Moreover, it is important to consider the effects of different waveforms on behavior, including the impulsive waves produced by sources such as pile drivers. If possible, such experiments should also be carried out under field conditions on naive animals; preliminary tests for this approach are currently in progress.

The initial results suggest that the sensitivity of crustaceans to substrate vibrations is sufficient to enable them to detect anthropogenic disturbances propagated through the seabed. Although detection of particle motion through the waterborne pathway may only be possible close to the source (Goodall 1988; Popper et al. 2001), crustaceans may be able to detect substrate vibrations at greater distances from the source.

6 Conclusions

The experimental method described was successful in establishing behavioral thresholds for the hermit crab *P. berhardus* to substrate vibration. The thresholds obtained begin to provide an understanding of the levels of vibration that could potentially cause behavioral changes in the natural environment, an area of research that has been neglected in recent years.

Sensitivity to vibration is particularly important in light of increasing marine developments around the coast. Many of these activities are likely to generate substrate vibrations in addition to producing waterborne sounds. There are also other natural sources of substrate vibration that may be of interest to animals living on the seabed. The effects of substrate transmission should not be overlooked when investigating the effects of noise pollution on the marine environment.

Acknowledgment Many thanks to Anthony Hawkins, Rafael Perez-Dominguez, and Samuel Cheesman for advice and the Department for Environment, Food, & Rural Affairs (Defra) for funding this work.

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Chapter 115
Parvulescu Revisited: Small Tank Acoustics for Bioacousticians

Peter H. Rogers, Anthony D. Hawkins, Arthur N. Popper, Richard R. Fay, and Michael D. Gray

Abstract Researchers often perform hearing studies on fish in small tanks. The acoustic field in such a tank is considerably different from the acoustic field that occurs in the animal's natural environment. The significance of these differences is magnified by the nature of the fish's auditory system where either acoustic pressure (a scalar), acoustic particle velocity (a vector), or both may serve as the stimulus. It is essential for the underwater acoustician to understand the acoustics of small tanks to be able to carry out valid auditory research in the laboratory and to properly compare and interpret the results of others.

Keywords Aquarium acoustics • Hearing threshold • Underwater hearing test facilities

1 Introduction

Nearly 50 years ago, Antares Parvulescu (1964, 1967) outlined the difficulties encountered when hearing experiments are carried out in small tanks of water having dimensions that are, of necessity, much smaller than an acoustic wavelength of the sound being used. The small size of the tanks, the large-impedance and

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sound-speed differences between the water and surrounding air, and the elasticity of the tank walls and support structure combine to make the acoustic field within the tank very complicated and difficult to model or even characterize. The problem is aggravated because the adequate stimulus for an aquatic animal may be acoustic pressure (a scalar), acoustic particle motion (a vector), or a combination of the two.

Parvulescu's papers (1964, 1967) had a strong influence on contemporary biologists. Strenuous attempts were made to resolve the problems of presenting measurable and interpretable sound stimuli to fish. Unfortunately, nowadays, Parvulescu's comments and recommendations have largely been forgotten or ignored. It has become commonplace for individuals studying fish bioacoustics to carry out hearing experiments in small laboratory tanks under inappropriate acoustic conditions and/or under conditions where the sound stimuli are not properly specified or measured.

In this chapter, we review and analyze the key points made by Parvulescu about experiments in small tanks and consider the conditions that must be achieved for measurements of the hearing abilities of fish to be considered valid. We consider both experimental data and theoretical models that illustrate and quantify the extent of these problems and, where possible, suggest methods for mitigating or accounting for them. We also include a discussion of fish hearing. Rather than continuously cite references, the reader is referred to Popper et al. (2003) and Ladich and Fay (2013) for appropriate backgrounds on fish hearing.

1.1 General Characteristics of Acoustic Fields

An acoustic field consists of pressure fluctuations (a scalar field) and particle motion (a vector field). The acoustic pressure is measured with a hydrophone in the water. The particle motion at any point in a fluid medium can be measured directly using a laser velocimeter or a neutrally buoyant accelerometer or it can be calculated from measurement of the pressure gradient vector.

The total energy contained in a sound wave consists of the sum of its potential energy (PE) and its kinetic energy (KE). The PE arises from the compression and expansion of the fluid and hence is related to the acoustic pressure, whereas the KE arises from fluid motion quantified by the acoustic particle velocity. In the absence of boundaries such as walls (the free-field condition), the sound pressure radiated from a simple acoustic source falls off as $1/r$, where r is the distance from the source. Far from the source (in the so-called far field), the energies associated with acoustic pressure and acoustic particle velocity are equal (KE = PE), whereas close to the source (in the near field), the particle velocity component of the field contains more energy (KE >> PE). At any distance from the source, the particle velocity vector is aligned with the direction to the source. In the presence of boundaries (e.g., at a wall, in room acoustics, or at the air-water interface in underwater acoustics), the situation is much more complicated and these simple relationships do not hold. For example, in room acoustics, at a wall, the particle velocity is nearly zero no matter where the source is located, whereas under water, the acoustic pressure approaches zero at the surface no matter where in the water the source is located.

2 Assessing Hearing Capabilities

To assess the hearing capabilities of any animal, terrestrial or aquatic, it is first necessary to characterize and quantify the acoustic field in the absence of the animal. The presence of the animal may alter the field significantly. The presence of a gas-filled cavity, for example, the swim bladder of a fish, may result in pressure release, generating higher particle motion and lower sound pressure. These field alterations may be important in ascertaining the hearing mechanism, but they are not relevant to the "calibration" of the auditory system.

Measurement of in-air hearing in terrestrial animals is relatively straightforward: the adequate stimulus is the acoustic pressure present at each ear. Due to the high mechanical impedance (density and stiffness) of tissue when compared with that in air, the acoustic particle motion vector cannot be detected by a single ear of a terrestrial animal.

The body of a fish is very similar in average density and stiffness to water. The body thus follows the acoustic fluid motion. The otolithic organs function like accelerometers to detect this motion, with each of the dense otoliths functioning as a "stationary mass." The sensory hair cells of the ear detect the relative motion between the tissue and the otolith, transducing individual components of the motion vector.

Experiments have demonstrated that the otolithic organs detect particle motion. Acoustic pressure detection requires the presence of a compliant element such as a swim bladder to transduce pressure into fluid particle motion, which can then be detected by the otolithic organs. In some species, the compliant element is close to the ear or mechanically coupled to it, whereas in others, rather weaker coupling is accomplished by an acoustic scattering mechanism. The mechanism by which a pressure signal is isolated from the individual acoustic particle motion components is not clear.

When a fish responds to a sound, it is not always certain whether it is responding to pressure, particle motion, or a combination of the two. Researchers have tried to shed light on this question by creating a sound field that contains only pressure or only particle motion. However, as pointed out by Parvulescu (1964), a fish's ability to detect a pressure signal may depend on the presence of a particle velocity signal or that the ability to detect particle motion (which contains all of the directional information) may depend on the presence of a pressure signal. There is some experimental evidence that this may be the case (Rogers et al. 2012).

Ideally then, in the interest of creating an appropriate stimulus, hearing in fish should be measured in an acoustic environment as close as possible to that of the animal's natural environment. That is, for a midwater ocean fish, hearing should be measured in a free field, and for a shallow-water fish, it should be measured in shallow water with an appropriate bottom and without sides other than a gradient that would simulate that found on a shore. This is the best way to ensure that the signals have the appropriate mixture of particle motion components (both vertical and horizontal) and pressure components. This, however, has rarely been done, most notably and successfully by European scientists in the 1970s working in midwater in the sea (e.g., Chapman and Hawkins 1973; Hawkins and Sand 1977).

Alternatively, as suggested by Parvulescu (1964), a specially designed rigid-walled, tubular sound exposure chamber with active termination (a sound projector at each end) allows both sound pressure and particle motion to be individually specified. In particular, such a chamber is capable of producing a traveling-wave (KE = PE) excitation if such a signal is appropriate. Traveling-wave tubes have been used for hydrophone calibration (Beatty et al. 1966), in fish hearing studies (Hawkins and MacLennan 1976), and in underwater noise exposure studies (Martin and Rogers 2008). Such chambers, however, are large, heavy, and expensive. (Note: A rigid-wall tube needs to be made of steel >3 cm thick. The tube used by Beatty et al. (1966) was made from the cannon barrel of an Iowa-class battleship. Those made by Hawkins and MacLennan (1976) and Martin and Rogers (2008) were of comparable thickness.)

Thus, for reasons of necessity, convenience, or economy, fish-hearing researchers end up resorting to acoustical configurations that are far from optimal.

3 Acoustic Fields in Small Tanks

Researchers who study hearing in fish and other aquatic animals often perform their experiments in small tanks or aquariums where the size of the tank is usually much smaller than the acoustic wavelength. The frequencies of interest are typically in the band from 50 to 1,000 Hz or so. Because the speed of sound in water is around 1,500 m/s, the wavelength ranges from 1.5 to 30 m. A 35-L aquarium has dimensions of ~26 × 26 × 51 cm and a 170-L aquarium is 44 × 44 × 88 cm. Thus, for either tank at all frequencies, all dimensions are smaller than the acoustic wavelength and in most cases much smaller. Although the glass tank walls may seem to form acoustic boundaries, they are, in fact, nearly acoustically invisible and the boundary condition at the tank walls (and for most tanks at the tank floor as well) is near zero pressure (pressure release; Parvulescu 1964). That is, to a first approximation, a fish tank behaves like a "brick" of water surrounded by air. When the acoustic source is in the water, the pressure must fall to zero at the walls, bottom, and surface. The particle velocity, however, does not. All six surfaces are nearly perfect sound reflectors. As a consequence, a single source within the tank creates hundreds of thousands of image sources, half of which would be positive and half negative due to the sign flip that occurs on reflection from a pressure release surface (see Parvulescu 1964). (Picture a room with mirrors on all four walls, the floor, and the ceiling.)

As an alternative to the use of image sources, a frequency domain of normal modes can be easily obtained (see Parvulescu 1964), but hundreds of thousands of modes are required. It turns out, however, that the small size of the tank greatly simplifies the solution. Because the acoustic wavelength is much larger than the tank dimensions, in the Helmholtz equation $\nabla^2 p = \left(\frac{2\pi}{\lambda}\right)^2$, p can be replaced by the much simpler Laplace's equation $\nabla^2 p = 0$, whose solution is independent of frequency. It turns out, therefore, that the solution to the Helmholtz equation is only weakly dependent on the frequency, and, in fact, the solution for the pressure in a

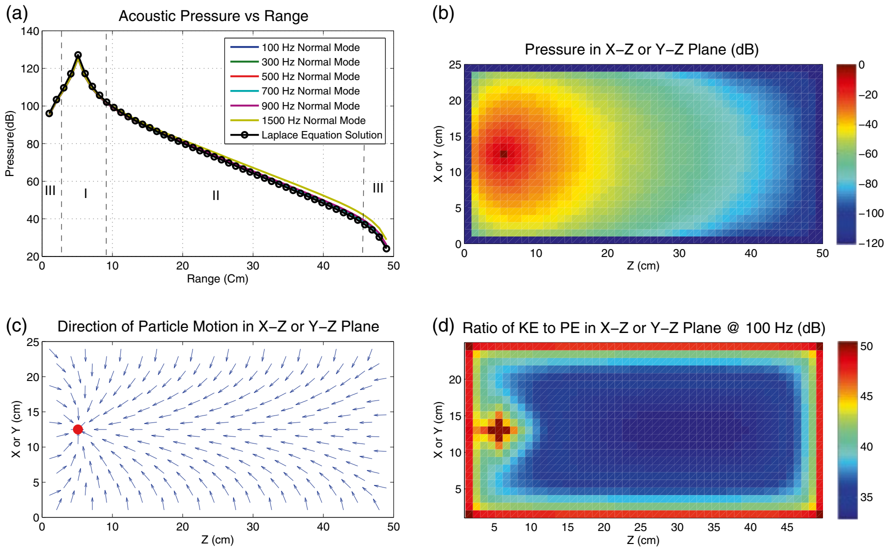

Fig. 115.1 Theoretical acoustic field for a 25- × 25- × 50-cm tank with a point source 5 cm from one end. (**a**) Pressure on the midline using normal-mode calculations at 100, 300, 500, 700, 900, and 1500 Hz compared with Laplace's equation results. (**b**) Laplace's equation for pressure in the *x*-*z* or *y*-*z* midplane. (**c**) Direction of fluid particle motion in the *x*-*z* or *y*-*z* midplane. (**d**) Ratio of the kinetic energy (KE) to the potential energy (PE) in the *x*-*z* or *y*-*z* midplane

35-L tank is virtually indistinguishable from the solution to Laplace's equation for frequencies up to 900 Hz or so.

In Fig. 115.1, we show calculated values for the acoustic field in a nominal 32-L tank (dimensions: L_x=25 cm, L_y=25 cm, and L_z=50 cm) with a point source located on the midline 5 cm from one end. Figure 115.1a shows a pressure scan along the midline calculated by solving the Helmholtz equation using 6,40,000 normal modes at six frequencies. The results are compared with a numerical solution to the much simpler Laplace equation. The Laplace equation solutions were obtained everywhere in the tank in just a few seconds on a laptop computer. For all frequencies up to 900 Hz, the differences were negligible, and even at 1,500 Hz, the differences were small. For the Laplace solution along a line from a source parallel to the long axis of the tank, the field falls off as $1/|z-z_s|$ near the source (Fig. 115.1a, I) and then decays exponentially as $e^{-\sqrt{\left(\frac{\pi}{L_x}\right)^2+\left(\frac{\pi}{L_y}\right)^2}\,z}$ (Fig. 115.1a, II; Akamatsua et al. 2002) before rapidly approaching 0 as the field point approaches either wall (Fig. 115.1a, III). Figure 115.1b shows the pressure field in the *x*-*z* or *y*-*z* plane passing through the source.

Although the Laplace analysis simplifies the nature and solution of the problem, it still yields results that differ significantly from the free-field results. For instance, the particle velocity no longer always points toward the source (see Fig. 115.1c) and the energy in the velocity field (KE) is much larger than the energy contained in the pressure field (PE). Figure 115.1d shows the ratio of KE to PE in the *x*-*z* midplane at 100 Hz. This ratio exceeds 32 dB everywhere. (Although the pressure is independent of the frequency, the corresponding particle velocity is not; it is proportional to the inverse of the frequency.)

Note that close to the surface where experiments involving neurophysiological and auditory evoked potential measurements are often performed, the ratio of KE to PE is enormous. Moreover, and independent of the location of the source, the particle velocity is always aligned with the vertical. In region II, along the midline of the tank, the pressure decay is exponential and hence the ratio of KE to PE is constant, although still very large. The results shown in Fig. 115.1 have been validated experimentally.

The effect of the fish on the field and the field on the fish was not explicitly considered by Parvulescu but is mentioned here. The fish's swim bladder (or any other bubble of air) is a strong acoustic scatterer, a fact that is used by many species to enhance high-frequency hearing and enable pressure detection. If the field is measured with the fish in the tank, the scattered field will also be included in the measured field. Close to the swim bladder (i.e., within a few swim bladder radii), the measured field will be higher than the actual stimulus field at and below the swim bladder resonance and lower above the resonance. We have verified this experimentally.

Sand and Hawkins (1973) have shown that Atlantic cod (*Gadus morhua*) maintain their resonance frequency above the simple air-bubble resonance frequency, thus keeping the depth-dependent resonance out of hearing range. Measuring the field with the fish present will thus generally result in an overestimate of the pressure threshold. The "mass" for the swim bladder resonance is provided by the entrained mass of the surrounding fluid. If the fish is too close to a tank surface, much of the entrained mass will be missing, resulting in a higher resonance frequency with concomitant effects on hearing sensitivity. As pointed out by Parvulescu and as we have seen, when the source is in the water, the ratio of pressure to particle velocity is unusually low compared with that seen in nature.

To create higher, more uniform sound pressures, Parvulescu (1964) suggested exciting the tank from the outside using loudspeakers, arguing that if a uniform exterior pressure can be created, the pressure within the tank would be uniform and relatively high. His reasoning was intuitively based, but the conclusion can be rigorously proved for an acoustically small tank. We have shown that the field within the tank satisfies Laplace's equation. It is well known (and easy to prove) that for a system obeying Laplace's equation, if the field variable on the boundary is uniform, the field variable must be uniform everywhere within the boundary. Thus, despite of the pressure release boundary, the pressure everywhere within the tank would be uniform and the particle motion would be zero. Parvulescu pointed out that it is no simple task to produce the required uniform excitation field given the relatively short wavelength of sound in air ($c_{\text{water}} = 4.5\, c_{\text{air}}$). It should also be pointed out that a high-pressure low-velocity condition never occurs in nature.

Another factor not discussed by Parvulescu is the effect of the elasticity of the tank walls. Although, at most frequencies, the thin glass wall of the aquarium is invisible, the walls can have significant effects on the interior field at and near its flexural (bending) resonances. For the thin glass walls of small tank, these resonances can fall within the frequency band of interest. The two lowest flexural resonance frequencies for the side and bottom plates of the 35-L tank, which are 6.3 mm thick (assuming free edges), are calculated to be 138 and 382 Hz, respectively. Both experiment and finite-element modeling indicate that the pressure field on the midline is enhanced at these frequencies. Interestingly, changing the walls from glass to steel makes almost no change in the flexural resonance frequencies because the higher stiffness of the steel is almost exactly offset by its higher density. The flexural resonance frequencies are proportional to the wall thickness, but the walls would have to be nearly 4 cm thick to raise the lowest frequency above 750 Hz. As discussed by Parvulescu (1964), it is impossible to treat an aquarium wall in such a way as to make it anechoic at low frequencies. It is, however, not difficult to provide a thin decoupling layer that will shield the walls and their resonances from the field in the water. The layer merely needs to be made from a very compliant material with a very low sound speed.

4 A Cautionary Tale for Bioacousticians

The practical significance for bioacousticians of these results is well illustrated by considering some acoustic pressure threshold data for Atlantic salmon (*Salmo salar*; Hawkins and Johnstone 1978) obtained under three very different acoustic conditions (see Fig. 115.2): (1) free-field conditions (middepth in deep water) at various ranges, (2) a small tank with the source in the water, and (3) a small tank with the source in

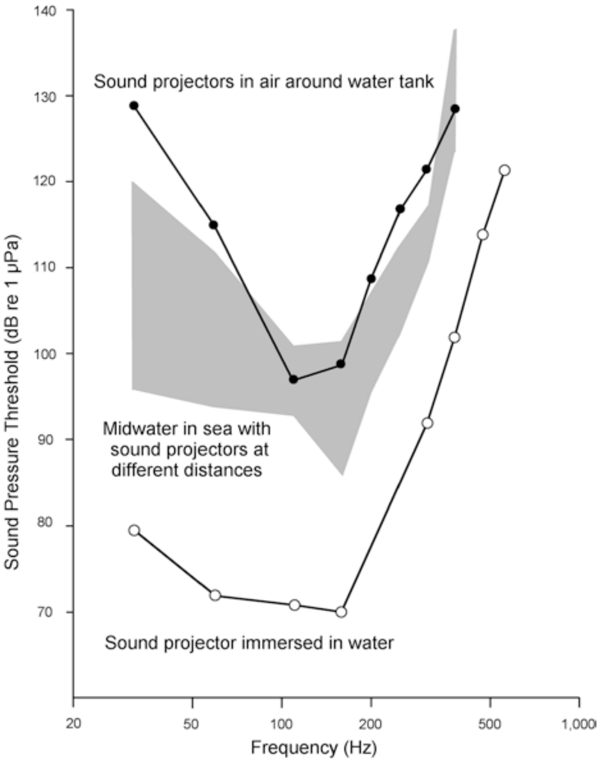

Fig. 115.2 Pressure thresholds for Atlantic salmon (*Salmo salar*) measured under three very different acoustic conditions. Note the large discrepancy in the observed thresholds

the air. For case 1, the ratio of KE to PE is a function of range and frequency with KE >> PE close to the source and approaching KE = PE at long-range or high frequency. For case 2, we have seen KE >> PE, whereas for case 3, we have seen PE >> KE. In all cases, a threshold is determined and stated in terms of pressure. The most obvious feature of Fig. 115.2 is that the thresholds measured in a small tank with the source in the air are much higher than the corresponding thresholds made in a small tank with the source in the water. If one were unaware of the nature of small-tank acoustics, one would be unable to explain the ~40-dB difference between the two results. However, with knowledge of small-tank acoustics, the obvious conclusion from this is that for case 3, the fish are responding to particle motion and not sound pressure. The pressure was small at the threshold, but pressure was not the relevant stimulus; the acceleration associated with the very large KE was.

5 Conclusions

Small tanks do not provide a suitable venue for fish-hearing experiments unless exceptional steps are taken to isolate the tank walls from the acoustic excitation and the tests are performed away from the tank boundaries. With care, they can provide a stable, easily modeled, reproducible acoustic field. However, it must always be kept in mind that in such tanks, the critical relationships between the acoustic pressure and the acoustic motion vector are very different to those that exist in a fish's natural environment. When excited by a source within the tank, the ratio of KE to PE of the field is much too large (and often the motion is in the wrong direction). When excited by loudspeakers located outside the tank, the KE-to-PE ratio is much too small. Thus, small tanks cannot be used to measure thresholds and make comparisons between species. They can, however, be used to compare changes within a single species that result from something done to a fish but only when the comparison is done under identical acoustic conditions (e.g., same tank, speakers) and when the fish are about the same size.

Acknowledgment This chapter is dedicated to the memory of Antares Parvulescu. Antares was a good friend and a consummate acoustician and scholar. He was a very rich intellect who enjoyed science and all other aspects of life. This work was supported in part by the Neely Endowment at Georgia Tech. We thank John Bogle of Georgia Tech for valuable finite-element modeling in support of this chapter.

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Chapter 116
Assessing the Underwater Ship Noise Levels in the North Tyrrhenian Sea

Eduardo Rossi, Gaetano Licitra, Andrea Iacoponi, and Daniele Taburni

Abstract The purpose of this research was to assess the anthropic underwater noise caused by ships within the Cetacean Sanctuary, a wide area in the North Tyrrhenian Sea. Noise from low-frequency continuous sounds has been investigated within the 1/3-octave bands centered at 63 and 125 Hz. All the information about noise sources and sound attenuation have been organized in a database; a tool automatically extracts useful information from it and feeds a ray-tracing model to estimate noise levels. The results show average levels generally over the 100 dB re 1 μPa value.

Keywords Ray tracing • Noise vessel • Cetacean Sanctuary

1 Introduction

The protection and safeguard of marine ecosystems require a careful analysis of the anthropic causes of habitat degradation. The increasing number of vessels and ships represents one of the most evident threats for marine organisms. The presence of naval routes within the boundaries of wide protected areas entails both direct and indirect hazards for marine life. Noise emissions from vessels represent one of the most important indirect hazards, which affect mainly the communication and

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orientation of cetaceans. In the last years, the scientific community focused on the physical injuries of marine mammals exposed to impulsive sounds such as sonar instruments deployed during naval exercises and seismic surveys for oil and gas exploration (Richardson et al. 1995; Gordon et al. 2004). However, impulsive sounds are quite different from what is typically produced by vessel engines. Sonars are characterized by high frequencies and high acoustic energy concentrated in time. On the other hand, naval emissions of noise are commonly described as continuous in time (i.e., not impulsive), with most of the energy confined below 500 Hz (i.e., low frequencies). As described by Jensen et al. (2011), these frequencies are not absorbed by the marine environment and so they can propagate quite far from the source of emission. Theoretically, the acoustic noise produced by naval engines and hulls could propagate over distances of thousands of kilometers. The main consequence of this scenario is an increase of 10 dB in the background levels in the last 30 years (Andrew et al. 2002; Cato and McCauley 2002; McDonald et al. 2006).

In June 2008, the European Community passed the Marine Strategy Framework Directive (European Commission 2008) to limit the rising noise pollution in the European seas caused by vessels. The directive identifies the noise values measured at 63 and 125 Hz (1/3-octave band) as appropriate indexes to evaluate the consequences of the marine traffic on the environment. If the sound levels averaged over 1 year exceed the threshold of 100 dB re 1 μPa root-mean-square (rms) at these two frequencies, it implies a polluted environment and a hazard for marine ecosystems.

Here, we evaluated the anthropic underwater noise caused by ships in the Cetacean Sanctuary, a 90,000-km^2-wide protected area in the North Tyrrhenian Sea within the framework of the Marine Strategy Framework Directive. This resulted in a coupling of a model of underwater sound propagation (Jensen et al. 2011) with information on the naval sources. The model-based approach represents a more powerful way to evaluate noise levels with respect to direct measurements with hydrophones. On the other hand, this approach requires that the initial information be completely operative. The main points are a full description of the sound propagation and attenuation in the environment (see Section 2), the localization in space and time of the acoustic sources (see Section 3), and the characterization of the emission spectra of the different vessels (see Section 3). This research represents one of the first examples of the assessment of naval noise pollution on a large spatial scale (hundreds of kilometers). The purpose here is to focus the attention of the scientific community on the limits and possibilities of such research, which will be plausibly even more requested in the future due to the rising levels of marine traffic.

2 Modeling Sound Propagation in the Underwater Environment

Sound propagation in the underwater environment is mainly affected by the interactions with the boundaries, both the sea surface and the seafloor, and by the fact that in the sea environment the sound speed profile (SSP) varies strongly with the depth.

This means that the acoustical wave is refracted in a complex way and that a study of the sound attenuation, i.e., transmission loss (TL), by simplified formulas may produce large errors in the estimation of the TL. So a numerical solution of the Helmholtz equation is required. In our study, the TL is modeled with the use of a well-known ray-tracing software, BELLHOP (Jensen et al. 2011; Porter 2011), which works on a bidimensional section (depth and horizontal range). At this stage, a good knowledge of the acoustical environmental features is required; bathymetry, seafloor morphology, and SSPs are all essential parameters to correctly run the model. The latter aspect, sound speed, has to be carefully studied because it may considerably affect the final results.

2.1 Environmental Description

The input parameters were stored in thousands of records in a SQL database. The bathymetry database was extracted from ETOPO1, a 1 arc-min global relief model of the Earth's surface. This model, provided by the National Geophysical Data Center (NGDC) of the National Oceanic and Atmospheric Administration (NOAA), integrates land topography with ocean bathymetry. For the area of study, the database was composed of 240,000 points. The SSPs were also obtained from the NGDC, recovering data about temperature, salinity, and depth collected within the area of interest during measurement campaigns, covering a period of almost 40 years. For each of the resulting 10,000 points, the database also includes the sampling date, the site coordinates, the bottom depth, and quality flags of sampled data. For the seafloor, we used geological maps of the seabed, reconstructing its geoacoustical properties, i.e., sediments sound speed, density, and attenuation.

2.2 SSPs

Sound speed represents one of the most important issues in underwater acoustics because it may considerably affect the propagation of the sound waves. Referring to the studies of Del Grosso (1974), Medwin (1975), Mackenzie (1981) and Leroy et al. (2008), it is evident how the sound speed values are strongly dependent on three main external parameters: temperature of the sea, salinity, and depth at which the sound speed is evaluated.

The first two parameters may change considerably in both the time scale and space due to different climatic or geographical conditions. With growing depth, the changes in temperature and salinity become less important, and in the deep isothermal layer, the hydrostatic pressure represents the leading parameter. The ray-tracing technique shows how solution of the eikonal equation is strongly dependent on the sound speed gradient along the water column. By rule of thumb, the presence of a sound speed inversion in the superficial layer may refract acoustical rays in deepness (summer); on the other hand, if the sound speed is a monotonic increasing function of the depth, most of the naval noise emissions are bounded in the shallow waters (winter). In this study, we are interested in an average description of the noise levels; this means that we should avoid fluctuations related to the particular weather conditions or geographical location presented at the time of the profile sampling. From a practical point of view, we need to define the best average profile for a given simulation section, starting from a finite number of sampling points. It should be stressed that these points were sampled during 40 years of activities so that the definition of the average needs to be done very carefully to avoid the introduction of bias or error, like averaging profiles belonging to different environmental conditions. The noise model BELLHOP (Jensen et al. 2011) was used to study statistically how the temporal and the spatial variabilities affect the TL values; thousands of simulations were performed using simple geometry environments, i.e., with flat homogeneous seafloors. The purpose of these simulations was to describe the shape of the SSP in terms of a quantitative descriptor (TL). The basic idea is that the evaluation of the TL in a fixed scenario will be nearly the same if two different profiles have almost the same shape. Using this difference in TL as an index of the difference in the shape of the SSPs, it is then possible to identify classes of similarity for profiles sampled in different periods of the year. The results of the statistical study show how the shape of the profiles are very stable during the winter and late summer periods throughout the years. On the other hand, the intrinsic variability of the environmental conditions during the spring and autumn make it more difficult to define an average SSP for a fixed day in these seasons, increasing the error in the final noise maps.

3 Modeling Ship Noise Emissions

To evaluate the sound pressure level at a certain depth, knowledge of the TL must be joined with a full analysis of the sources, i.e., of the naval noise emissions. This basically means (1) knowing the position in time of each vessel within the Cetacean Sanctuary and (2) knowing the emission spectra of acoustic energy for each ship.

The position in time of each vessel was determined using the signals coming from the automatic identification system (AIS). AIS is a maritime safety network of antennae installed onboard ship, which provides the longitude and latitude coordinates every few seconds for all the main vessels. We used AIS data from the NATO Undersea Research Centre (NURC) at La Spezia relative to the year 2009; the entire database contains 26 million records.

If, on one hand, it is evident how the knowledge of the spectra emissions for such a large number of ships is practically impossible, on the other hand, what is really important is to provide a general description of the spectra for the main typologies of vessels at different speeds. Data from the literature were combined with specific measurements made by ARPAT in the years 2011–2012 using Poseydon, an oceanographic vessel equipped with a digital hydrophone. We finally described five classes of ships (passengers, cargo, tanker, yacht, and tugs) at three

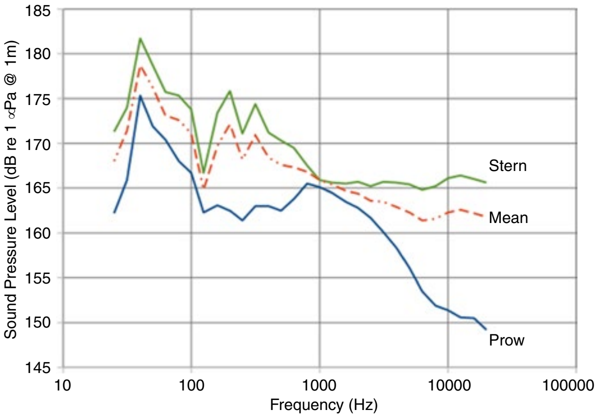

Fig. 116.1 One-third octave band spectrum of a tanker measured near the coastline of Leghorn. The spectrum is corrected by the transmission loss (TL) that was present between the ship and the hydrophone. The spectrum clearly shows the difference in shape between a stern and a prow measurement due to the strong directivity. In this study, a weighted logarithmic average of stern and prow spectra was used to characterize the mean spectrum of each single boat

different speeds (5, 15, and 25 kn). This database of acoustical emission spectra will be enhanced with future measurement campaigns. An example of the measured spectra is shown in Fig. 116.1.

4 Results

All the information collected Sections 2.1, 2.2, and 3 needs to be organized efficiently to get the noise levels as an output; all the noise maps are evaluated automatically by a PHP software system that manages all the input parameters. TL is totally independent from the naval source. It describes the attenuation of a sound at a given frequency between a starting point (SP) and a receiver point (RP). It is dependent on the environment (sound speed profiles, bathymetry, and seafloor and water absorption). We evaluated the TL between thousands of couples of SP-RP for each day of the year to describe the attenuation of the sound in the entire area of the Cetacean Sanctuary. At the end of this stage, the entire area is covered with a spatial grid of TLs that provides us with information on the attenuation of sound with depth and distance relative to specific couples of SR-RP.

Starting from this spatial grid, we interpolated a TL value for each AIS point in the period of interest with respect to all the RPs. The sound pressure level produced by each vessel in a single RP is then subtraction of the interpolated TL from the emission spectrum. It should be noted that this subtraction occurs at a fixed frequency (63 or 125 Hz, following the Marine Strategy Framework Directive) and that each vessel is characterized by its own spectrum that depends on the typology of the ship and the speed.

If we are interested in evaluating the noise produced in a single receiver (j) on a monthly scale (T_{month}) by all the vessels (i), the following formula can be used

$$L^{j}_{month} = 10\ \log_{10}\left[\frac{1}{T_{month}}\left(\sum_{i=1}^{N} 10^{\frac{L_i}{10}}\ T_{\text{sec}}\right)\right]$$

where L_i refers to the level produced by the i vessel in the j receiver and T_{sec} is the time between an AIS datum and the following one. In fact, each vessel is described with a certain number of AIS points that describe its movements along the route (on a monthly time scale they can be hundreds or thousands). The underlying assumption here is that the acoustical emission of the ship is constant between each AIS point, which is not so unlikely considering that the emission of an AIS datum is much faster than the typical changes in speed of the vessels.

If this operation is repeated for all the receivers, a full description of the sound pressure levels within the entire area of the Cetacean Sanctuary is possible. In Fig. 116.2, a noise map for the frequency of 125 Hz is reported as an example; there were 37 receivers at a depth of 1,000 m.

One of the most interesting features of our software system is its flexibility. In fact, the number of RPs, the frequency, and the depth at which the noise maps were evaluated can be easily changed by the external user. It is obvious that the greater the number of RPs, the greater the accuracy and computational costs.

A few words about the overall uncertainty associated with the estimation of the noise levels in the maps. Each step in the assessment of the noise (evaluation of TL and the spectra) incurs a certain amount of error; the most relevant of these is the evaluation of the spectra emissions of the vessels. This is due to the small number of spectra considered to describe the large number of vessels that are actually present in our database. The global uncertainty is ~8 dB given the current number of

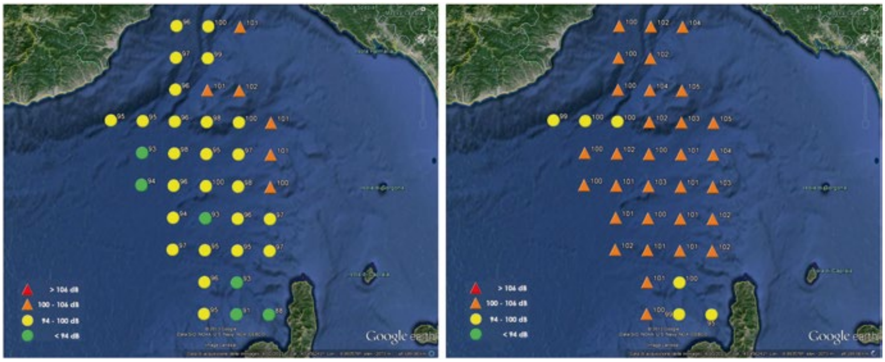

Fig. 116.2 Comparison between estimated average noise levels in January (*left*) and June (*right*). Noise levels were calculated at a depth of 1,000 m at a frequency of 125 Hz. Color legend is parameterized on the threshold of 100 dB re 1 μPa, as suggested in the Marine Strategy Framework Directive (European Commission 2008). The grid size for this particular simulation is 16 km. Both the step of the grid size and the depth of analysis can be modified by the user

ships in the database of emission spectra. From statistical considerations, we think that doubling the number of measured spectra could reduce the overall error value of the error to 4–6 dB.

5 Conclusions

The software system described represents one of the first steps in the challenging field of the estimation of the underwater noise in extended environments. It shows promising features for the study of the noise produced by vessels in the Ligurian Sea; theoretically, it could work within the range of 65–20,000 Hz at all the desired depths, showing a high versatility. We think that it could be an useful tool for marine biologists interested in the study of the effects of human noise on cetacean life because it follows a balanced approach (possible and enough detailed for the scope) to give an answer to the regulations coming from the EU Marine Strategy Framework Directive.

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Chapter 117
Radiated Sound of a High-Speed Water-Jet-Propelled Transportation Vessel

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Abstract The radiated noise from a high-speed water-jet-propelled catamaran was measured for catamaran speeds of 12, 24, and 37 kn. The radiated noise increased with catamaran speed, although the shape of the noise spectrum was similar for all speeds and measuring hydrophone depth. The spectra peaked at ~200 Hz and dropped off continuously at higher frequencies. The radiated noise was 10–20 dB lower than noise from propeller-driven ships at comparable speeds. The combination of low radiated noise and high speed could be a factor in the detection and avoidance of water-jet-propelled ships by baleen whales.

Keywords Ship radiated noise • Whale • Water-jet propulsion • Ship strike

1 Introduction

In August 2007, the Hawai'i Superferry started service between the ports in Honolulu, Oahu, and Kahalui, Maui. The MV Alakai was an aluminum hull "drive-on, drive-off" catamaran ferry designed by Austal USA. The ferry was powered by four MTU 20 V 8,000 M70 engines with two KaMeWa 125 s 11 water-jets used for propulsion. The ferry's maximum speed was 40 kn. The Hawai'i Superferry was highly controversial due to environmental and legal concerns. Even before the first voyage, the Hawai'i Supreme Court ruled that the Hawai'i Department of Transportation had made errors on the Superferry environmental impact assessments (EIAs). Operations were temporarily suspended and then allowed to resume multiple times. Finally, a court order was issued in March 2009 to permanently suspend operations and in June of the same year, the Hawai'i Superferry declared bankruptcy. Since then, the Alakai and its sister ship, the Huakai, were purchased by

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the US Maritime Administration in 2012 and both vessels were transferred to the US Navy for use as high-speed transport vessels (Kerrigan 2012). The Navy has since renamed the two vessels as the USNS Puerto Rico and USNS Guam and will be using them for the transport of troops and motorized vehicles.

The two main issues of concern for the impact of a high-speed water-jet-propelled vessel to cetaceans are the impact of noise and the possibility of ship strikes (Kubota 2007). As part of the 2009 EIA, measurements were taken of the radiated noise at different speeds to estimate the acoustic impact of the Alakai and to determine its detectability and possible impact on humpback whales in Hawai'i. This study discusses the results of those noise measurements and their implications for cetacean management.

2 Methods

The radiated noise from the Hawai'i Superferry Alakai was measured in the vicinity of Honolulu Harbor. Measurements were made in three comparable locations to minimize alterations to the ferry's normal route and operational procedures. Measurements were performed with the Alakai making passes past the recording vessel at 12, 24, and 37 kn. The Alyce C, a 32-ft sport fishing vessel, was used as the recording platform. The water depth was 54 m for the 12-kn measurement, 215 m for the 24-kn, and 250 m for the 37-kn measurements.

The pattern of the Alakai's route was chosen so that the noise radiating from the bow, broadside, and stern aspects could be measured. A similar trajectory was used for all three runs at different speeds. GPS positions from both the Alakai and the Alyce C were used to calculate the distance between both vessels as a function of time.

Acoustic measurements were conducted with four hydrophones located at different depths recorded simultaneously on two synced digital recorders. Two spherical hydrophones were used, an International Transducer Corporation model 1,032 and an Edo Western model (both with outside diameter 7.6 cm, sensitivity of −194 dB re 1 V/μPa over a 40-kHz range). The transducers at 10 and 20 m were custom-built hydrophones with spherical piezoelectric ceramic elements housed in cylindrical packages including preamplifiers. Both were high-frequency hydrophones that could function at frequencies up to 200 kHz. The hydrophone at 10 m depth had a sensitivity of −185 dB re 1 V/μPa and the one at 20 m had a sensitivity of −175 dB re 1 V/μPa. Two Microtrack digital recorders operating at a sample rate of 44.1 kHz with 16 bits were used. The recorders were turned on simultaneously, and a calibration noise was made to provide a more precise synchronization signal to each hydrophone measured.

The root-mean-square (rms) sound pressure level (SPL) at the receiving boat was calculated with the following equation

$$p_{rms} = \sqrt{\frac{1}{T}\int_0^T p(t)^2 \; dt} \tag{1}$$

where $p(t)$ is the instantaneous acoustic pressure (p) as a function of time (T). An integration time of 1 s was used to determine the SPL as a function of time for the entire recording period for three hydrophones. Unfortunately, the fourth hydrophone at a depth of 20 m malfunctioned so data were not recorded. To calculate the source levels (SLs) of the radiated noise from the Alakai at different aspects (bow, broadside, and stern), the GPS tracks from the Alakai were used to determine the time at which the ferry would have its bow directed (within 10°) toward the hydrophone array, when it would be broadside, and when it would have its stern directed within 45°. Once the appropriate times were determined, the distance between the two vessels was calculated and the received SPL could be referenced to 1 m with the following equation

$$SL_{1m} = SPL_{rec} + 20\log(R) \tag{2}$$

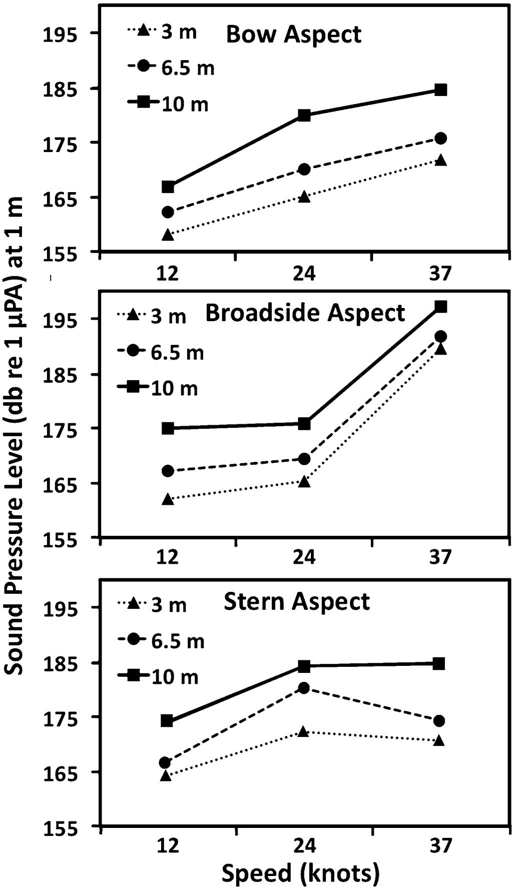
This equation assumed spherical spreading of the acoustic energy, which is an approximation of the sound propagation. Due to the short ranges, simple propagation of the radiated acoustic energy was sufficient, and detailed modeling of the propagation is beyond the scope of this project.

3 Results

At the closest approach, the ferry was nearly broadside to the hydrophone array. The SL as a function of speed is shown in Fig. 117.1 for the three different aspects of the Alakai with respect to the three hydrophones at depths of 3, 6.5, and 10 m. The hydrophone at the 10-m depth always measured the loudest sounds for the three speeds of the Alakai. The reason for this may be due to propagation effects near the surface. The intensity of the vessel sounds generally increased with speed except for two situations in the stern aspects involving the hydrophones at 3 and 6.5 m depth. The radiated sound measured broadside to the Alakai had the highest intensity at all speeds, 12–15 dB higher than at the bow and stern aspects. The radiated sounds from the bow and stern had very similar intensity values. The loudest SPL (200 dB re 1 μPa) occurred at the broadside aspect with the Alakai traveling at a speed of 37 kn.

The frequency spectra of the radiated sounds with the ferry traveling at 37 kn are shown in Fig. 117.2 for the hydrophone at the 10-m depth. All of the spectra depicting the radiated noise at speeds of 12, 24, and 37 kn were similar at all depths and consisted of broadband noise with a low-frequency peak at ~200 Hz and decreased continuously at higher frequencies. There were no tonal signals recorded during vessel passes. Although most boats typically have distinguishing acoustic characteristics between 0 and 5 kHz, only broadband noise was evident in these lower frequencies and had a hisslike quality to the human ear.

Fig. 117.1 Source level of radiated noise at the three hydrophone depths listed as a function of speed and aspect of the ferry



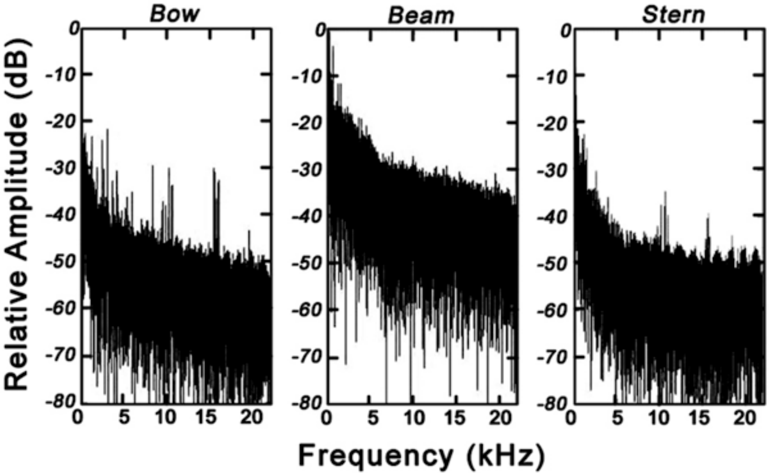


Fig. 117.2 Frequency spectra of the radiated noise from the Alakai traveling at 12, 24, and 37 kn as measured by the hydrophone at a depth of 10 m. Low-frequency noise was also broadband with no distinguishing acoustic features. Spectra were computed with a fast Fourier transform (FFT) algorithm within MATLAB, using a rectangular window and 44,100 points or 1 s worth of data

4 Discussion and Conclusions

The intensity of the radiated sounds increased with depth from 3 to 10 m. The only explanation for this characteristic is the propagation of a low-frequency noiselike signal originating close to the surface to other locations also close to the surface. It is beyond the scope of this study to examine the propagation of broadband sound from a surface craft to distant locations near the surface. However, it is important to be aware that baleen whales are air-breathing animals that typically spend time close to the surface of the ocean and that a whale at the surface presents the greatest problem for potential ship strike. A surface vessel will pass over a whale that is deeper than the draft of the ship.

Our measurements suggest that the noise radiated from a jet-propelled ship is lowest in the bow aspect. Unfortunately, when a ship approaches a group of whales, it will have its bow pointed at the whales, presenting a challenge for the whales not only to detect an oncoming ship but also to recognize that it is an oncoming ship and that it presents a potential danger. The detection, recognition, and response process may occur only as the oncoming ship is very close to the animals so that evasive action by the whales may not be possible.

Measurements of the radiated noise from high-speed vessels propelled by water-jets are on the order of 10–20 dB lower in intensity than propeller-driven ships traveling at comparable speed (Allen et al. 2012; Mckenna et al. 2012). It is difficult to predict the distance at which baleen whales can detect a boat-radiating noise in the same frequency range of hearing as whales. Unfortunately, there are no current measurements for the hearing of large whales, but we can calculate the distance at which the radiated noise from the oncoming vessel is louder than ambient noise. This ambient noise will vary depending on time and location. In the waters of the Hawaiian Islands during the humpback whale winter season, the intensity of chorusing humpback whales can be high (on the order of 110–120 dB). The lower noise level could be a potential problem involving collisions with baleen whales. Ships such as the Alakai may not be heard by baleen whales until the separation distances are so short that the animals cannot take evasive action. At low speed, the radiated noise will decrease but so will the range at which whales can detect an oncoming ship. In addition to humpback whales, right whales and other large baleen whales are species of concern because these vessels will be used in a variety of locations.

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Chapter 118
Impact of Anthropogenic Noise on Aquatic Animals: From Single Species to Community-Level Effects

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Abstract Anthropogenic noise underwater is on the rise and may affect aquatic animals of marine and freshwater ecosystems. Many recent studies concern some sort of impact assessment of a single species. Few studies addressed the noise impact on species interactions underwater, whereas there are some studies that address community-level impact but only on land in air. Key processes such as predator–prey or competitor interactions may be affected by the masking of auditory cues, noise-related disturbance, or attentional interference. Noise-associated changes in these interactions can cause shifts in species abundance and modify communities, leading to fundamental ecosystem changes. To gain further insight into the mechanism and generality of earlier findings, we investigated the impact on both a predator and a prey species in captivity, zebrafish (*Danio rerio*) preying on waterfleas (*Daphnia magna*).

Keywords Anthropogenic noise • Temporal patterns • Swimming behavior • Foraging performance

1 Background

Aquatic animals can be negatively affected by anthropogenic noise in many ways (Richardson et al. 1995; Popper et al. 2003; Popper and Hastings 2009; Slabbekoorn et al. 2010). Artificial exposure to extreme sound pressure levels (SPLs) may cause direct harm in physical damage and physiological stress. Artificially elevated but

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more moderate levels may also lead to harassment through physiological stress and especially to a range of behavioral responses that may be detrimental but also beneficial by escaping or reducing further more-damaging exposure (Slabbekoorn 2012). Behavioral responses may include spatial deterrence and interruption of critical activities such as feeding, courting, or spawning. Many species also rely on biologically relevant sounds for orientation, navigation, communication, predator avoidance, and prey detection. Masking of these biologically relevant sounds can also have a detrimental impact to which animals cannot habituate.

Studies in birds have revealed a noise impact beyond single-species effects (Francis et al. 2009, 2012). Noisy and quiet extraction sites of the gas and oil industry in North America have provided unique study material to investigate the effects of noise, independent of confounding factors that are typically associated with urban locations or highways. Francis et al. (2009) have shown that besides direct and negative effects on breeding density for some species, there may also be indirect and positive effects for others. They convincingly showed that a prominent egg predator for small bird species was less common at extraction sites with noisy generators (24/7) than at identical extraction sites without the additional presence of anthropogenic noise. As a consequence, typical prey species were more abundant at the more noisy sites due to predator release. Slabbekoorn and Halfwerk (2009) argued that similar dynamics may also be found among competitor species as in the case of selective deterrence with one species being more sensitive than the other.

In a remarkable follow-up study, Francis et al. (2012) showed that species interactions had an even much broader taxonomic width. The egg predator of the first study also happened to be a seed disperser, caching seeds of trees for harvesting later in lean times. Typically, many seeds are forgotten with this habit and food cachers usually have a strong effect on the distribution of tree seedlings. The study indeed revealed an indirect noise impact on vegetation structure due to the direct impact on this seed-dispersing species and the lack of impact on a seed-eating mammal.

2 Noise Impact Underwater Beyond Single-Species Effects

Noise impacts on species interactions that can lead to community-level effects are also possible underwater in various ways (Fig. 118.1). Selective deterrence can lead to declines for some species and inclines for others, e.g., for avian predators and prey or competitors in air. Disturbance can affect stratification of pelagic predators and prey species at various trophic levels, which may lead to shifts in foraging efficiency and predation risk. Disturbance can make bivalves, crustaceans, and small benthic fish retract or hide, affecting their own foraging efficiency and the food availability to their predators. Masking may affect the appropriate settlement of fish and crustacean larvae, directly affecting predation risk and opportunities for feeding and hiding. Masking and deterrence may affect the appropriate habitat associations and migratory efficiency for adult fish and marine mammals, directly affecting

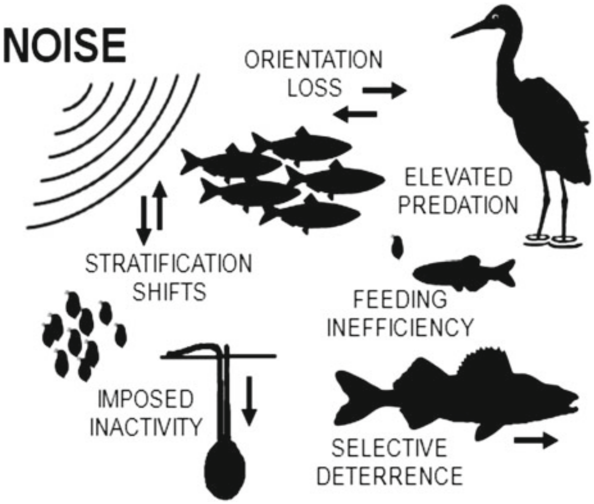

Fig. 118.1 Several examples through which anthropogenic noise may cause shifts in relative species densities in horizontal and vertical directions. Anthropogenic noise may have consequences that go beyond single-species effects. Species interactions among predators and prey or among competitors may be affected in various ways and have cascading effects through different trophic levels in the underwater food chain

predation risk and opportunities for exploiting food sources and reproductive potential. And finally, although this is not meant to be an exhaustive list, masking and attentional interference may reduce both prey alertness for predators and predator foraging efficiency on prey.

In underwater communities, effects of pollutants other than noise have already been shown to go beyond single-species effects. Turbidity can affect visibility and have a detrimental effect on one species through interference with efficient foraging or courtship (Gray et al. 2011), and not on the other, which may yield shifts among competitor species. Water turbulence has been shown to affect the handling time of prey in the green crab (*Carcinus maenas*), which may be bad for predator and good for prey (Gabel et al. 2011). Chemical pollution has also been shown to have direct effects on one or several species, which subsequently cause a cascade of effects through the food web of the system (Fleeger et al. 2003).

Purser and Radford (2011) investigated how foraging performance is affected by brief and prolonged periods of elevated noise levels on captive three-spined sticklebacks (*Gasterosteus aculeatus*). They found that the playback of anthropogenic sound not only influenced swimming behavior via an increase in startle response but also that the sound exposure resulted in decreased prey attack efficiency and increased food-handling errors. They did not test the variation of impact related to temporal patterns in sound exposure and they also did not investigate whether the noise-related change in foraging efficiency was due to an effect on the predator alone or also through an effect on the prey behavior.

3 Current Study and Implications

We studied the impact on both predator and prey for zebrafish preying on waterfleas. We tested sound exposure conditions that varied in temporal pattern: continuous, regular and irregular intermittent, and control with no additional sound exposure. We checked for a noise impact on (1) waterfleas swimming behavior, (2) zebrafish swimming behavior, and (3) foraging behavior and efficiency of zebrafish hunting for waterfleas. We found (1) no significant effects of sound exposure on waterfleas, (2) that temporal pattern affected the response to sound exposure in the fish, and (3) that the detrimental impact of sound exposure on feeding efficiency was independent of temporal pattern.

Our study confirms the possibility of noise impact beyond single-species effects underwater. The impact on foraging efficiency in predator fish feeding on invertebrate prey may alter the balance in abundance between the two taxa. The direct impact seems to be on the predator but that will not exclude an indirect impact on the prey. More research is needed on the direct and indirect effects of anthropogenic noise on species interactions. Especially the accumulating consequences for shifts in relationships among local community members warrant future study efforts.

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Chapter 119
Identifying Variations in Baseline Behavior of Killer Whales (*Orcinus orca*) to Contextualize Their Responses to Anthropogenic Noise

Filipa I.P. Samarra and Patrick J.O. Miller

Abstract Determining the baseline behavior of a whale requires understanding natural variations occurring due to environmental context, such as changes in prey behavior. Killer whales feeding on herring consistently encircle herring schools; however, depth of feeding differs from near the surface in winter to deeper than 10 m in spring and summer. These variations in feeding depth are probably due to the depth of the prey and the balance between the costs and benefits of bringing schools of herring to the surface. Such variation in baseline behavior may incur different energetic costs and consequently change the motivation of whales to avoid a feeding area. Here, we discuss these variations in feeding behavior in the context of exposure to noise and interpret observed responses to simulated navy sonar signals.

Keywords Behavioral variations • Feeding • Killer whales • Sonar

1 Introduction

The effects of anthropogenic noise on different marine species, particularly those such as marine mammals that make extensive use of the acoustic sensory mode to communicate, have been a cause of increasing concern (e.g., Nowacek et al. 2007). In cetaceans, anthropogenic activity, particularly military sonar exercises, has been linked to deleterious population effects such as mass strandings (e.g., Frantzis 1998). Behavioral responses to noise can change considerably, ranging from changes in

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sound production (e.g., DeRuiter et al. 2013a) to an interruption of behaviors such as foraging and prolonged changes in diving behavior (e.g., Tyack et al. 2011; DeRuiter et al. 2013b). Responses to anthropogenic sound as well as their severity has been a subject of intensive study, particularly through conducting controlled exposure experiments (e.g., Miller et al. 2011). Correct classifications of the severity of behavioral responses rely on accurate identification of functional behavioral categories. Proper characterization of typical behavior patterns during baseline behavior allows interpretation of observed behavioral disturbances as part of a common repertoire. Furthermore, the ability to accurately identify functional behaviors, such as feeding, allows the assessment of whether these behaviors might be disturbed, increasing our ability to judge the potential biological consequences of exposure to anthropogenic sound. Additionally, the type and magnitude of behavioral responses to anthropogenic noise may be strongly influenced by the behavioral and environmental context of exposed individuals (Ellison et al. 2012; Miller et al. 2012). For example, deep-feeding blue whales responded to exposure to simulated navy sonar by ceasing feeding, whereas surface-feeding animals showed no change in behavior (Goldbogen et al. 2013). Therefore, it is necessary to take into account natural variations in behavior when identifying and interpreting responses to noise.

Killer whales (*Orcinus orca*) in Norway follow the migration of their main prey, the Norwegian spring-spawning herring (*Clupea harengus*; Stenersen and Similä 2004). In winter, killer whales could be found in a narrow fjord system in northern Norway feeding on large aggregations of overwintering herring that gathered there in high densities (Similä et al. 1996). Their "carousel-feeding" behavior employed when feeding on overwintering herring has been studied considerably (Similä and Ugarte 1993; Shapiro 2008). However, their herring prey is known to change its schooling behavior as it changes its life stage from overwintering to feeding and spawning (Nøttestad et al. 1996). Whether and how the feeding behavior of killer whales may vary throughout the year is less well understood. In winter, naval sonar exercises have occasionally occurred in the same area occupied by the whales and their herring prey, and the observed responses of killer whales to such exercises have included abandoning the feeding ground for several days (Kuningas et al. 2013). The concerns of the effects of these exercises in the local killer whale population was part of the motivation of the 3S project, a behavioral-response study aimed at understanding the effects of navy sonar on killer whales as well as on sperm whales (*Physeter macrocephalus*) and long-finned pilot whales (*Globicephala melas*; Miller et al. 2011). The 3S project is described in Chapter 71 by Lam et al. As a result of this project, killer whales were exposed to simulated navy sonar during different times of the year, particularly during winter in the Vestfjorden basin and in spring in offshore waters. On two occasions, once in winter and once in spring, killer whales were identified to be feeding before exposure to sonar. In both cases, killer whales interrupted feeding and avoided the sound source (Miller et al. 2011, 2012). Here we consider known natural variations in the feeding behavior of killer whales in the interpretation of their responses to simulated navy sonar signals.

2 Methods and Results

Using high-resolution multisensor archival tags (Dtags; Johnson and Tyack 2003) we characterized the feeding behavior of herring-eating killer whales to identify natural variations across seasons. The tags have a pressure sensor and 3-axis magnetometers and accelerometers sampling at a rate of 50 Hz, later down-sampled to 10 or 5 Hz, and 2 hydrophones sampling at 96 or 192 kHz. Pressure data were converted to depth in meters (with a resolution of 0.5 m between 0 and 2,000 m; Johnson and Tyack 2003) using calibrated values. Feeding-related sounds (called “tail slaps”; Simon et al. 2005) were used as indicators of feeding attempts, and movements during feeding were characterized by angle deviations in the heading data. We deployed 16 tags in Norway in winter and spring and in Iceland in summer. We observed that across seasons killer whales consistently used an encircling behavior during feeding, presumably to gather their herring prey into compact schools to facilitate prey capture. This behavior likely increases the efficiency of tail slaps by ensuring that the herring school is more compact and more herring will be affected by the action of the slap. However, the depth at which feeding occurred changed across seasons. Although in winter killer whales seemed to feed close to the surface, in spring and summer, feeding often occurred deeper than 10 m.

During the 3S project, two killer whales (oo06_327s and oo09_144a) were exposed to simulated navy sonar signals while feeding. Details of the exposure protocol, deployment characteristics, and behavioral responses were described by Miller et al. (2011, 2012). In both cases, the presence of tail slaps in the acoustic record of the tags as well as surface behavior observations before the start of the exposure were used as an indication of feeding (Miller et al. 2011, 2012). In both cases, the whales were observed to interrupt feeding and started a clear avoidance response to the source (Miller et al. 2011, 2012). The whale oo06_327s exposed to a low-frequency active sonar (LFAS; 1–2 kHz) signal while feeding on overwintering herring responded at a received maximum sound pressure level ($\mathrm{SPL}_{\mathrm{max}}$) of 139 dB re 1 μPa, whereas the whale oo09_144a exposed to sonar while feeding on herring during its feeding life stage responded to midfrequency active sonar (MFAS; 6–7 kHz) at a received $\mathrm{SPL}_{\mathrm{max}}$ of 94 dB re 1 μPa (Miller et al. 2011, 2012). Two additional individuals were tagged and exposed to simulated sonar signals in 2006 (oo06_317s) and 2008 (oo08_149a); however, oo06_317s was determined not to be feeding before exposure, whereas the behavior of oo08_149a was difficult to interpret and therefore was excluded from this discussion.

3 Discussion

The most likely explanation for the observed seasonal variations in the feeding behavior of killer whales is differences in prey behavior across the seasons. Herring school size, density, and preferred depth varies considerably between winter, spring, and summer (Nøttestad et al. 1996). In winter, herring schools form large aggregations with very high densities, which are not seen at other times of the year (Nøttestad et al. 1996). In spring, herring form small, dispersed schools that are actively feeding at diverse depths in the water column. Finally, during summer spawning periods, herring form multiple breeding aggregations along the seafloor. These variations in prey behavior and distribution likely drive differences in details of foraging parameters, including depth of foraging. Variations in prey density and behavior also likely change the foraging energetic costs and benefits to the whales as would seasonal differences in the nutritional value of the herring. Presumably, the energetic requirements of feeding will vary between winter and spring because the depth of feeding may represent increased costs for whales feeding deeper than whales feeding near the surface. Proximity to the surface will allow whales to perform shorter and shallower dives with reduced transit and a higher proportion of time feeding (Nøttestad and Similä 2001). In addition, feeding on herring when its distribution is patchy in comparison to the winter is also likely to affect the potential energetic consequences of leaving a herring school. Therefore, we might hypothesize that killer whales feeding on herring at different life stages may exhibit different motivations for avoiding a feeding area due to the energetic requirements of prey capture at different depths, differing food value of individual prey, and the distribution and density of prey schools encountered.

The two examples of sonar exposures of killer whales differed in the location, environmental context, exposure signal, and season (Miller et al. 2011, 2012). Despite the observed differences in feeding behavior between winter and spring, the response in both cases was similar, resulting in the interruption of feeding and prolonged avoidance of the sound source. Although this may suggest that the motivation of whales to abandon a food patch would be similar at different times of the year, despite the presumed differences in energetic requirements of the different feeding behaviors, consideration of the prey availability is lacking. In 2006, the amount of overwintering herring found in the fjords of northern Norway had decreased dramatically in comparison to previous years (Kuningas et al. 2013). In fact, observed changes in the distribution of the killer whales in this area seem to be related more strongly to the availability of prey than to exposure to sonar and the responses to real navy exercises seemed to vary between years of high and low prey abundance (Kuningas et al. 2013). Thus, it is possible that the habitat quality (i.e., prey availability and distribution) in the two experiments mentioned above did not differ as much as expected if the winter availability and distribution of herring had remained as in previous years. Although there is no information on the herring school size and behavior being fed on by the whales in the two seasons, it is possible that this was similar between seasons and that the decreased availability of prey during the winter of 2006 made its distribution patchier. This shows that it is necessary to consider not just natural variations in the behavioral context of exposed animals but also the environmental context and particularly habitat quality that may contribute to the motivation to respond when interpreting responses to anthropogenic noise.

Although these examples show that killer whales feeding on herring at different times of the year apparently responded to sonar exposure in a very similar way, more replicates are necessary to fully understand how patch quality might influence the likelihood of an avoidance response that is associated with abandonment of a prey patch. As evidenced in other species, there can potentially be considerable variation in responses to sound exposure even within the same behavioral context (Goldbogen et al. 2013). Nevertheless, it is possible that regardless of the energetic costs of different feeding behaviors, killer whales will have a high motivation to interrupt feeding in response to exposure to navy sonar signals. Identifying variations in baseline behavior helps us interpret behavioral responses to noise but these should be coupled with assessments of habitat quality, particularly the availability of prey.

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Chapter 120
A Brief Review of Cephalopod Behavioral Responses to Sound

Julia E. Samson, T. Aran Mooney, Sander W.S. Gussekloo, and Roger T. Hanlon

Abstract Sound is a widely available cue in aquatic environments and is used by many marine animals for vital behaviors. Most research has focused on marine vertebrates. Relatively little is known about sound detection in marine invertebrates despite their abundance and importance in marine environments. Cephalopods are a key taxon in many ecosystems, but their behavioral interactions relative to acoustic stimuli have seldom been studied. Here we review current knowledge regarding (1) the frequency ranges and sound levels that generate behavioral responses and (2) the types of behavioral responses and their biological relevance.

Keywords *Sepia officinalis* • Cuttlefish • Sensory ecology • Hearing • Squid

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1 Introduction

Sounds are abundant in the ocean. They are produced by a range of organisms (e.g., fish, crustaceans, mammals) and by abiotic conditions (e.g., wind, waves, rain, earthquakes). Underwater sounds travel relatively fast (~1,500 m/s), can be detected over long distances (Urick 1983), and are often available when sensory cues such as light or chemical stimuli may be limited (Popper and Hastings 2009). It is well established that many marine vertebrates detect and use sound for vital activities such as navigation, foraging, predator detection, and reproduction (Fay and Popper 1999; Au et al. 2000). The ability of marine invertebrates to detect and potentially use sound is far less understood, which is somewhat surprising given their relative abundance and central role in many aquatic ecosystems (Budelmann 1992a, b; Boyle and Rodhouse 2005).

Sound detection in cephalopods was first reported by Baglioni (1910), who noted that octopuses reacted to low-frequency acoustic vibrations and water movements. Later publications included the description of behavioral (Dijkgraaf 1963; Komak et al. 2005), physiological (Kaifu et al. 2007), conditioned (Packard et al. 1990), and neurological (Hu et al. 2009; Mooney et al. 2010) responses to sound stimuli of different frequencies and intensities.

The organs generally thought to enable sound detection in cephalopods are the statocysts (Hanlon and Messenger 1996; Kaifu et al. 2008). These are paired organs located in the cartilage below the brain. They consist of a fluid-filled cavity containing a macula-statolith system for the detection of linear acceleration (e.g., gravity) and a crista-cupula system for the detection of angular acceleration (e.g., movement; Budelmann 1975). Polarized hair cells are found in both the macula and the crista systems (Budelmann 1979). The component of a sound field likely perceived by cephalopods is particle acceleration, not sound pressure (Packard et al. 1990; Mooney et al. 2010). In addition to the statocysts, *Sepia officinalis* (European common cuttlefish) also has lines of epidermal hair cells running over the head and arms that detect local water displacement (Budelmann et al. 1991; Hanlon and Messenger 1996). Their contribution to sound detection is poorly understood.

In the past decades, the development and greater use of the ocean have led to a concurrent increase in anthropogenic noise (National Research Council 2005). This noise may stem from many sources including shipping and vessel traffic, sonar systems, seismic air guns, and oil drilling. Our increased awareness of the influences of anthropogenic noise on the marine environment has led to several scientific studies addressing its potential impacts on diverse marine life (e.g., Mooney et al. 2009; André et al. 2011; Fewtrell and McCauley 2012).

Cephalopods play an important role in ecosystems and are a key component of food webs, providing a vital link from smaller invertebrates and fish to marine megafauna, birds, and humans (Boyle and Rodhouse 2005). It is therefore important to investigate the potential impact of increased anthropogenic noise on cephalopods. Changes in the behavior and distribution of cephalopod populations could have substantial impacts on the survival and distribution of top predators such as marine mammals, sharks, and sea birds; such changes would also impact commercial fisheries (Boyle and Rodhouse 2005). In this paper, we review research regarding cephalopod behavioral responses to sound, placing these studies in the context of potential noise impacts. In particular, we address the frequency and sound level ranges that generate behavioral responses in cephalopods, the types of behavioral responses elicited, and their biological relevance.

2 Behavioral Responses to Various Acoustic Stimuli

Cephalopods have a broad behavioral repertoire, including body movements (arms, mantle), body pattern changes, locomotor responses (jetting, fin movements), and inking (Hanlon and Messenger 1996). Multiple ethograms have been published (e.g., Hanlon and Messenger 1988; Hanlon et al. 1999 and references therein) and these provide the framework for future experiments in which behavioral responses to acoustic stimuli can be observed, recognized, and categorized in a quantitative manner.

Figure 120.1 summarizes the cephalopod responses to sound. Dijkgraaf (1963) reported jetting, darkening of the skin, and narrowing of the pupils in *S. officinalis* in response to taps on the tank walls. Body patterning changes were observed when using 180-Hz tones. Juvenile cuttlefish exhibited changes in body patterning, displacements, and burrowing when exposed to local sinusoidal water motion from 20 to 600 Hz (Komak et al. 2005). Certain frequencies generated substantially higher levels of activity in juvenile animals. Unfortunately, the stimulus intensities (measured as sound pressure level or particle motion) were not reported. Recently, using acoustic stimuli ranging from 80 to 1,000 Hz and a range of sound levels (measured in both sound pressure and particle acceleration), Samson et al. (2014) categorized the behavioral responses of *S. officinalis* to different tones. The responses included fin movements, body pattern changes, startle, jetting, and inking. Reactions considered

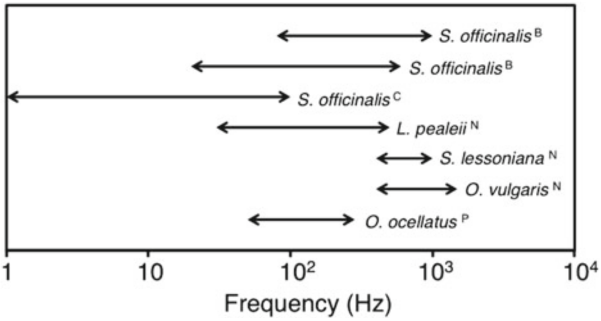

Fig. 120.1 Sound detection ranges for several cephalopod species determined using behavioral (*B*), conditioned (*C*), or neurological (*N*) responses. References: Samson et al. (2014); Komak et al. (2005); Packard et al. (1990); Mooney et al. (2010); Hu et al. (2009); Kaifu et al. (2008)

to be escape and/or startle behavior (blanching, jetting, inking) mostly occurred at low frequencies and high sound levels. The average sound level needed to elicit a certain response varied for each sound frequency.

Similar escape responses have been observed in squid, *Sepioteuthis australis*, exposed to seismic air gun noises. The animals showed inking and jetting behaviors and increased swimming speed and swam upward, possibly to benefit from the sound shadow near the water surface (McCauley et al. 2000; Fewtrell and McCauley 2012). In *Octopus ocellatus*, Kaifu et al. (2008) reported changes in respiratory rates during exposure to sounds of 50–283 Hz. Although octopuses are also capable of body pattern changes, jetting, and inking, those behaviors were not mentioned in the literature as responses to sound stimuli.

3 Potential for Habituation to Acoustic Stimuli

Studies on the potential for habituation of cephalopods to any kind of stimulus are scarce; most research on the learning capabilities of these animals has focused on memory and spatial learning (e.g., Karson et al. 2003; Agin et al. 2006). Visual habituation to a predator model has been observed in the squid *Lolliguncula brevis* (Long et al. 1989); the squid showed a decrease in body pattern changes and jetting with repeated presentation of the fish models. Visual and tactile habituation were also demonstrated in *Octopus vulgaris*; the animals showed long-term habituation to visual stimulation using a prey model and a decrease in object handling over time (Kuba et al. 2006).

Cephalopod habituation to acoustic stimuli has yet to be addressed in detail. Only a few notes on the subject, collected en passant during previous studies on sound detection in cephalopods, have been found in the scientific literature. Dijkgraaf (1963) mentioned a very quick habituation to a 180-Hz tone in *S. officinalis*; after only one exposure, the animals would not react to the stimulus anymore. Using juvenile *S. officinalis*, Komak et al. (2005) obtained opposite results: no habituation was observed to repeated stimuli of different frequencies ranging from 40 to 600 Hz.

After behavioral tests to different sound frequencies and levels, Samson et al. (2014) exposed *S. officinalis* to repeated sound exposures at 200 Hz and different sound levels. A potential for habituation was observed; response intensity decreased, but response extinction was not reached during the time of the experiments.

4 Future Research Directions

Studying behavioral responses along with physiological, conditioned, or neural responses is a productive way forward to determine the function of sound in cephalopod life history. Physiological responses, for example, can provide information on

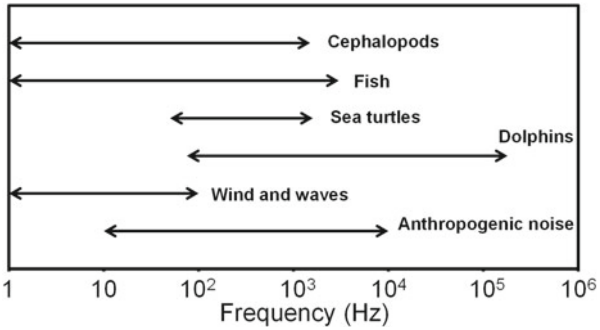

Fig. 120.2 Hearing ranges of several marine organisms in comparison to two important abiotic sound sources in the ocean. References for cephalopods are listed in Fig. 120.1. References: Popper and Hastings (2009); Piniak et al. (2012); Au et al. (2000); Wenz (1962)

the detection ranges and thresholds (Hu et al. 2009; Mooney et al. 2010) but not on the use of sound by organisms and the role it plays in vital behaviors such as feeding, defense, or reproduction. Behavioral responses may also reveal cephalopod functional use of sound stimuli. Moreover, knowing how animals respond to sound is important from an ecological point of view (Hanlon and Shashar 2003) and should enable us to predict the disruptive effects of anthropogenic sounds on population behaviors (e.g., migration, spawning) and ecosystems because there is substantial overlap among the hearing ranges of many key organisms and the range of anthropogenic noise in the ocean (Fig. 120.2). It is unclear which type of acoustic information influences cephalopod ecology given the low frequencies to which they react and the absence of behavioral responses to ultrasonic clicks typical of odontocetes, a prominent group of cephalopod predators (Wilson et al. 2007).

Microscopic studies have shown that the hair cells in the statocysts and epidermal lines of *S. officinalis* and other cephalopods are polarized (Budelmann 1979; Budelmann et al. 1991). This characteristic of the hair cells could be the anatomical basis for directional hearing and sound location in cephalopods. The ability to sense the direction of acoustic stimuli and the location of acoustic sources has likely functions in defense but could also play roles in other behaviors including navigation. Investigating these potentials in cephalopods might shed light on important aspects of their sensory ecology.

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Chapter 121
Effects of Model Formulation on Estimates of Health in Individual Right Whales (*Eubalaena glacialis*)

Robert S. Schick, Scott D. Kraus, Rosalind M. Rolland, Amy R. Knowlton, Philip K. Hamilton, Heather M. Pettis, Len Thomas, John Harwood, and James S. Clark

Abstract Right whales are vulnerable to many sources of anthropogenic disturbance including ship strikes, entanglement with fishing gear, and anthropogenic noise. The effect of these factors on individual health is unclear. A statistical model using photographic evidence of health was recently built to infer the true or hidden health of individual right whales. However, two important prior assumptions about the role of missing data and unexplained variance on the estimates were not previously assessed. Here we tested these factors by varying prior assumptions and model formulation. We found sensitivity to each assumption and used the output to make guidelines on future model formulation.

Keywords Missing data • Body condition • Process error • Bayesian • Photo identification

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1 Introduction

North Atlantic right whales (*Eubalaena glacialis*) are an endangered species, and despite many years of protection, their population is recovering at an extremely slow rate (Kraus et al. 2005). This rate of recovery is much lower than that in congenerics and leaves them vulnerable to natural and anthropogenic disturbance. These disturbances can include climate change, ship strike, entanglement with fishing gear, and, putatively, acoustic disturbance. Some of these disturbances yield immediate and obvious signals, e.g., death, massive propeller scars, and entanglement scars (Knowlton et al. 2012; Moore et al. 2012). However, in many cases, the effect of the disturbance is sublethal and not immediately obvious. To address this, researchers at the New England Aquarium have developed a method for using photographs to classify visual parameters reflecting the apparent health of individual right whales (Pettis et al. 2004; Rolland et al. 2007). Recently, Schick et al. (2013a) developed a hierarchical Bayesian model that uses this photographic evidence of health to infer the latent health status of individuals. This model provides estimates of the latent or "true" health at a monthly time step for each of the right whales in the North Atlantic Right Whale Catalog (Hamilton and Martin 1999). Although this approach effectively assimilates many different sources of data, it did not assess the effect of prior assumptions on the results. Here we address this limitation by exploring the effect of two components of the model detailed in Schick et al. (2013a): (1) the impact of missing visual health data on the estimates of true health and (2) our assumptions about how much the health of an individual can vary in a given month.

Body condition plays an important role in many ecological processes, and monitoring the energetic stores of individuals can provide fundamental information about their health (Schick et al. 2013b). The condition of right whales has been determined via direct and indirect measurements of blubber reserves (Pettis et al. 2004; Miller et al. 2012). Although somewhat limited in resolution, body condition determined from photographs is a crucial health indicator for right whales. For example, only 1 out of 14 whales that have been scored as "very thin," the worst category, has been known to survive (Pettis et al. 2004). Schick et al. (2013a) used this visual health parameter (VHP) to inform individual health estimates. However, efforts to quantify health can be augmented through the inclusion of additional visual parameters, including skin condition, presence of cyamids on the blowhole, and rake marks forward of the blowhole (Pettis et al. 2004). Schick et al. (2013a) proposed an effective observation submodel to handle the ordinal observations and link them to the process model for latent health, which was estimated on a continuous scale. Each of these four VHPs contributes to a deeper understanding of the health status in individual right whales (Schick et al. 2013a).

Understanding baseline health in the face of multiple sources of uncertainty is a critical first step when examining the effect of a disturbance (Schick et al. 2013b; New et al. 2014). One of these uncertainties is missing data because of the difficulty in obtaining continuous field observations of large whales. Although new tools are being developed [e.g., fecal hormone assays (Hunt et al. 2006; Rolland et al. 2012)], at present, right whale researchers have an incomplete picture of individual whale health status. For example, there may be a photographic observation of skin condition but a missing observation for body condition. In cases of missing and/or incomplete data, one can make use of a statistical technique known as multiple imputation (Rubin 1987). Although Schick et al. (2013a) used multiple imputation, they did not test alternative formulations to the model for missing data. Estimating process variance is often a difficult task, and informative prior assumptions are often used in Bayesian settings (Clark 2007). Schick et al. (2013a) used an initial naive informative prior assumption for health process variance but did not assess the impact of this assumption on the estimates of health. Using new data on the rate that individual right whales can change body condition classes (H. Pettis, unpublished manuscript), we can now assess this impact. This is important because it will inform practitioners whether apparent declines in health are real or simply artifacts of the data and modeling process.

Statistical models can be effective inferential tools to link observations of health to latent states of health; however, it is important to perform sensitivity analyses to better understand the effect of assumptions on the inference. Here we address this by examining the impact of two assumptions in the model from Schick et al. (2013a). Understanding these impacts will lead to model refinement and a better understanding of how disturbance may impact the health of individual right whales.

2 Methods

The model from Schick et al. (2013a) is a state-space model linking visual ordinal observations of health to a latent, or true, continuous health state. There is a process model for true health, which provides monthly estimates of health on a 0–100 scale. In addition, there is a process model for individual movement, which provides an estimate of the animal's location each month. There are data models that link each of four visual health parameters to the continuous health estimates. Finally, there is a model for individual survival that is a function of health and region. Inference is Bayesian within a Gibbs sampling framework (Clark 2007).

For an animal in any given month, there are typically many missing data observations (see an example in Fig. 121.1, top). To account for this, Schick et al. (2013a) used a multiple-imputation approach. A prior assumption was set on the imputation with the assumption that the animals' overall health time series is likely to be most indicative of its current health status for the body condition health parameter. That is, if an animal is most often seen as "thin" throughout its life, then the prior assumption for a missing body condition observation is weighted most heavily to imputing a missing observation in this same class. To test the effect of this assumption, we investigated two additional formulations for missing data. The first was to use a prior assumption that was weighted by the nearest (in time) sightings before and after the current time as follows. Let us assume that we are imputing missing body condition data. This VHP has three ordinal classes: very thin (1), thin (2), and not

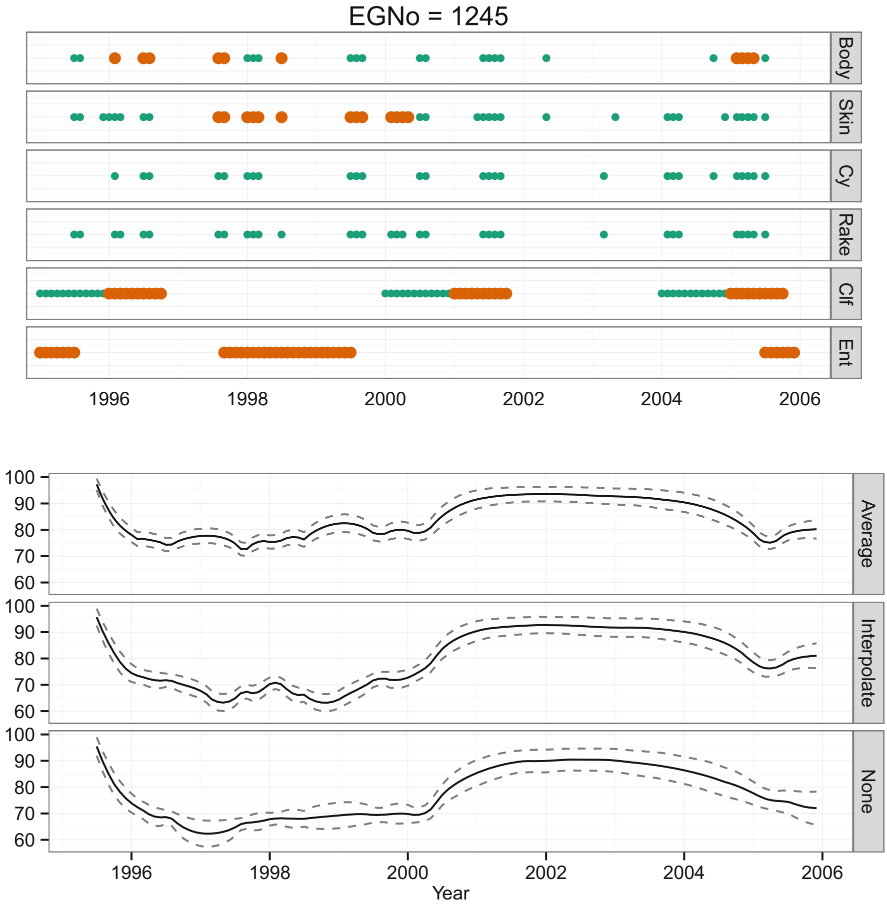

Fig. 121.1 Observed data (*top*) and estimates of health (*bottom*) for one individual, EGNo 1245. *Top*: four visual health parameters (body condition [Body], skin condition [Skin], presence of blowhole cyamids [Cy], and presence of rake marks [Rake]) and two additional data types that are not included in the model (calving status [Clf] and entanglement status [Ent]). Each *dot* represents a sighting with an assigned ordinal value for each health class. For the four visual health parameters, the size and color of the *dot* corresponds to severity, i.e., *small green dots* indicate good condition and *large orange dots* indicate medium condition. *Green* in the calving panel represents the pregnancy year; *orange* represents the lactation period. *Orange dots* in the entanglement panel depict periods during which the animal was entangled. *Bottom*: health (*thick lines*) and 95% Bayesian credible intervals (*dashed lines*) under three assumptions about the missing data: Average imputation, Interpolated missing data, and None (no imputation). See text for further details

thin (3). Therefore, we want to stochastically draw a value of 1, 2, or 3 to replace the missing observation. We used the last known observation and the next known observation to provide probabilities for this draw. If the animal was last seen in class 3 and at the time of its next sighting was also in class 3, then the draw from a multinomial distribution uses probabilities in Table 121.1, column 5. Conversely, imag-

Table 121.1 Lookup table used in the second missing data imputation for body condition

	Probability				
Class	Column 1	Column 2	Column 3	Column 4	Column 5
1	0.714	0.364	0.143	0.182	0.143
2	0.714	0.364	0.143	0.182	0.143
3	0.143	0.182	0.143	0.364	0.714

Values in each column refer to the probabilities used in the prior assumption for imputing the missing value. For example, if the missing data are presumed to be close to class 1, then column 1 is used. If the missing data value is presumed to be close to class 2, then column 3 is used. Column 2 is used when the missing data value is likely to be class 1 or class 2

ine that an animal has been observed in different health classes between its last and next observations. Now we linearly interpolate between these known end points and draw from a multinomial accordingly. If the missing observation is close in time to a body class 3, then we may draw from Table 121.1, column 5. If the missing observation is instead closer to a known body class 2, then we will draw from Table 121.1, column 3. In the intervening times, we have an increasing chance of drawing from Table 121.1, column 5, then column 4, and then column 3. The second approach was to use no data imputation. We tested the effect of these two formulations for missing data and compared them against the results from Schick et al. (2013a).

After accounting for the relationship between covariates and health, there is a residual unexplained variance in the health process. Through the use of an informed prior assumption, Schick et al. (2013a) set upper bounds on this variance to 15 health units/month. To test the assumptions about process variance, we reran the model with the default set of parameters, varying only the health process variance. We tested values of 4, 8, 12, and 16 on the prior estimates for health.

3 Results

We found a significant effect of both missing data imputation (Fig. 121.1) and process variance (Fig. 121.1) on the estimates of health. For missing data, choosing no imputation leads to a lower overall estimate of health (Fig. 121.1). In addition, during periods when there are no health observations, the estimates of health become less certain (Fig. 121.1). For higher monthly process variance, using a higher variance allows a much more rapid apparent recovery from periods of poor health (Fig. 121.1). Conversely, as the amount of unexplained variance each month was reduced, the relative change in health between time periods was much slower (Fig. 121.1).

The effect of missing data imputation was striking. We found four important differences in (1) the range of health values, (2) the start and end values, (3) the credible intervals, and (4) the health estimates during periods of missing data. First, in the imputation method using the average of the animal's health over the time series,

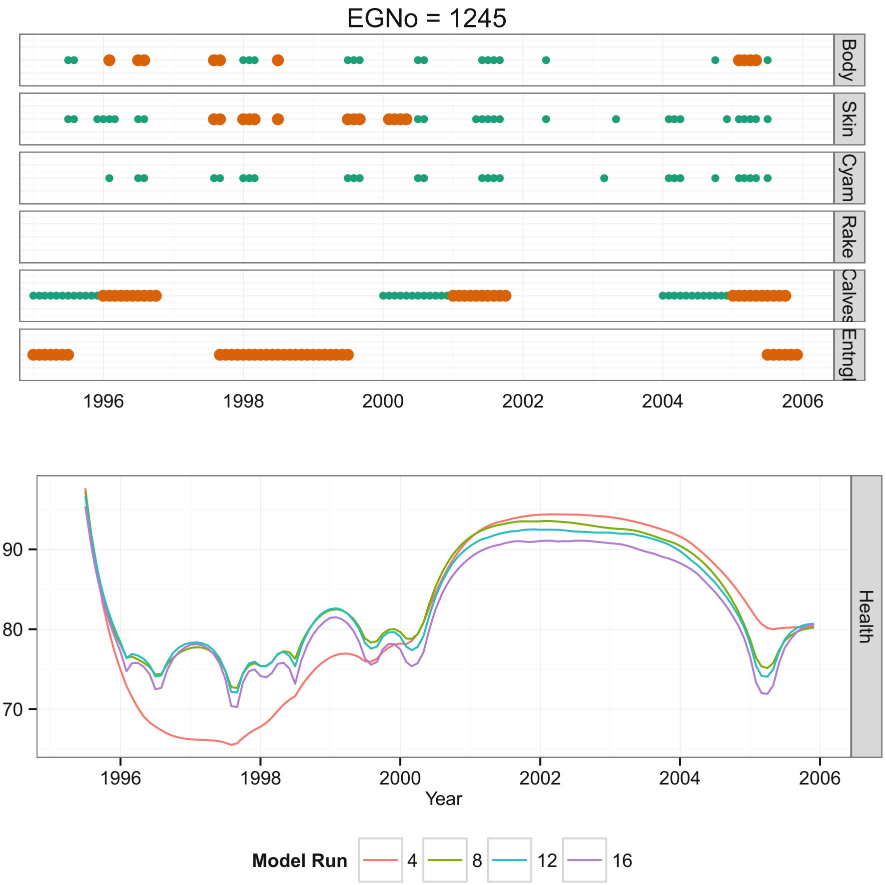

Fig. 121.2 Observed data (*top*) and estimates of health (*bottom*) for one individual, EGNo 1245. *Top*: four visual health parameters (body condition [Body], skin condition [Skin], presence of blowhole cyamids [Cyam], presence of rake marks [Rake]) and two additional data types that are not included in the model (calving status [Calves] and entanglement status [Entng]). Each *dot* represents a sighting with an assigned ordinal value for each health class. The size and color of the *dot* corresponds to severity, i.e., *small green dots* indicate good condition and *large orange dots* indicate medium condition. *Bottom*: four different estimates of health that vary as a function of the process variance used. As monthly process error is reduced, health varies much more slowly

the overall health is much higher and there is a narrower range of health. In contrast, in the interpolated and no imputation schemes, the overall health value goes much lower (Fig. 121.1). Second, in both imputation schemes, the first and last estimates of health are higher than in the no imputation scheme. Third, as would be expected when we do not impute missing data (Clark and Bjørnstad 2004), the overall Bayesian credible intervals around health are much broader. Finally, in two periods of missing data (mid-1996 to mid-1997 and mid-1998 to mid-1999), we see significantly different estimates of health from the method of Schick et al. (2013a; Fig. 121.1). When we imputed missing data using the average of the whole time series, then health recovered in these two time periods, whereas when we do not impute missing data, there are no changes in health in these periods. For example, in Fig. 121.1, “Average” panel, health recovers in January 1997 to around 77, whereas in the “None” panel, health at this same time is around 64. In addition, during these periods of missing data, we see broader confidence intervals around the median estimates of health (Fig. 121.1).

The overall trend of the health estimate is similar at different variance values, yet three important differences emerged (Fig. 121.2). First, when we restricted the amount of unexplained error in the process model to 4 units/month, the minimum and maximum health estimates were lower (66) and higher (94), respectively, compared with higher amounts of process variance. Second, when we restricted the variance to 4 units/month, the month-to-month change in health was very smooth (Fig. 121.2). What this means is that animals do not “recover” between periods of known health; instead, their health changes much more slowly. There are two periods where this is especially obvious: mid-1996 to mid-1997 and mid-1998 to mid-1999 (Fig. 121.2). Third, at values of 8–16, the trend in health was quite similar (Fig. 121.2).

4 Discussion

We have shown the effects of two prior assumptions on the estimates of individual health in North Atlantic right whales. The results indicate that the treatment of missing data and process error variance both have significant influence on prior estimates of health. In particular, with no imputation, we estimated health dips during periods of missing data and we estimated health with greater uncertainty (Fig. 121.1). With small process variance, the health estimates followed a very smooth trend and range both higher and lower than with larger variances (Fig. 121.2). Both of these findings have important implications for modeling the health of right whales.

In this modeling exercise, we were after a baseline understanding of individual health. This baseline will provide a critical reference point for assessing changes in health that come as a result of anthropogenic disturbance. Accordingly, we needed to understand how the baseline estimates were affected by our model assumptions. The results show that our baseline estimates can have notably different values based on our treatment of the missing data (Fig. 121.1). During periods of missing data, health estimates can point to health recovery or decline (Fig. 121.1). There is likely no “right” way to treat these data gaps; instead, the range of treatments allows for better biological understanding.

Because variances can be difficult to estimate in Bayesian settings, informative prior assumptions are often used (Clark 2007). These results have shown that the estimates of individual health are sensitive to this assumption and that the health trajectory varies significantly based on changes in the health process variance. As with missing data, there is likely no one "right" variance before use; instead, running the model over a range of these prior assumptions has allowed us a better understanding of a biologically valid range of values to use. In addition, running the model on well-known individuals with extensive life history data allowed us to test the ability of the model to reflect known biological characteristics. We have settled on a monthly process variance of 10 because this represents a good balance between our understanding of the input data and the biological responses we estimated during this exercise. We recommend that anyone taking this type of approach to health monitoring repeat this exercise to flesh out the link between photographic observations of health and the true latent health state.

As the development of offshore marine renewables continues and as shipping traffic increases (Conn and Silber 2013), right whales will face increased disturbance, both acoustic and from interactions with ships. Because mammalian health is directly linked to reproductive success and survival, baseline health assessments are needed to evaluate the impact of future disturbance. We tested two important components of a health model and found that the choice of prior assumptions and model formulation for missing data have a significant influence on the estimates. We argue that these tests are critical for a broader and more complete understanding of health and helped provide a useful framework for future tests on the effects of disturbances on health.

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Chapter 122
Auditory Effects of Multiple Impulses from a Seismic Air Gun on Bottlenose Dolphins (*Tursiops truncatus*)

Carolyn E. Schlundt, James J. Finneran, Brian K. Branstetter, Jennifer S. Trickey, Victoria Bowman, and Keith Jenkins

Abstract Auditory thresholds were measured in three bottlenose dolphins before and after exposure to ten impulses from a seismic air gun. Thresholds were measured using behavioral and electrophysiological methods to determine the amount of temporary threshold shift induced. The results suggest that the potential for seismic surveys using air guns to cause auditory effects on dolphins may be lower than previously predicted; however, two of the three dolphins exhibited "anticipatory" behavioral changes at the highest exposure condition that suggested they were attempting to mitigate the effects of the exposures.

Keywords Temporary threshold shift • Hearing • Noise

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1 Background

Although limited data exist regarding marine mammals exposed to single impulsive sounds, no temporary threshold shift (TTS) data exist for marine mammals exposed to multiple impulses. To investigate the auditory effects of multiple underwater impulses, auditory thresholds were measured in Atlantic bottlenose dolphins (*Tursiops truncatus*) before and after exposure to a series of impulses produced by a seismic air gun. The pre- and postexposure hearing thresholds were compared to determine the amount of TTS as a function of exposure conditions.

2 Methods

Three bottlenose dolphins participated in the experiments: BLU (female, ~45–46 years at the time of testing, ~200 kg), TYH (male, 30–32 years, 200 kg), and OLY (male, 27–29 years, 200 kg). TYH's upper cutoff frequency was ~120–130 kHz; however, OLY had high-frequency hearing loss above ~70 kHz, and BLU had substantial high-frequency hearing loss above 40–50 kHz. The high-frequency hearing loss in OLY and BLU is not unusual for dolphins of their age (Houser and Finneran 2006).

The air gun was a Sercel G-Gun 150, with an adjustable volume from 40 to 150 in.^{3}. The water depth at the test site in San Diego Bay was ~7 m and the air gun was deployed at a depth of 2 m. On exposure days, the subjects were exposed to a sequence of ten impulses, delivered at a rate of one impulse every 10 s over a 90-s interval. On control days, no impulses were fired but the subjects remained on an underwater station for the same 90-s interval in front of the air gun as during the exposure sessions (mock exposure). A total of eight different exposure conditions or "levels" (configurations of volume, pressure, and range, i.e., distance between the air gun and the subject) were used during the study. The levels, configurations, number of control and exposure sessions conducted, and ranges of mean cumulative sound exposure levels (SELs; for ten impulses) measured for the three subjects are provided in Table 122.1. At the highest exposure levels, there was much more variation in the range of received levels, particularly for TYH and OLY, when behavioral reactions to the exposures were observed.

Before and after each (mock) exposure sequence, hearing thresholds were measured at several frequencies using psychophysical (behavioral) and electrophysiological (auditory evoked potential [AEP]) methods. Postexposure thresholds were then compared with their preexposure values to determine the amount of TTS induced. After no substantial differences were seen between the post- and preexposure thresholds, the exposure level was increased (the dolphin was moved incrementally closer and/or the air gun pressure/volume was increased) on the next exposure day and the process was repeated. Exposure conditions were repeated over a number of days to provide replicates and to test multiple frequencies after each exposure condition.

Table 122.1 Levels, configurations, number of control and exposure sessions conducted, and ranges of mean cumulative sound exposure levels measured for BLU, TYH, and OLY

Exposure level	Range (m)	Volume (in.^{3})	Pressure (psi)	Control sessions	Exposed sessions	Peak-to-peak SPL (dB re 1 μPa)	rms SPL (dB re 1 μPa)	Cumulative SEL (dB re 1 μPa^2·s)
1	7.9	40	1,000	41	9	193–197	170–174	175–176
2	7.9	40	2,000	22	13	198–203	173–179	178–182
3	7.9	150	1,500	1	4	198	175	180
4	7.9	150	2,000	16	18	199	176	180
5	3.9	40	1,000	27	17	202–206	182–185	186–189
6	3.9	40	2,000	6	4	209	186	191
7	3.9	150	1,500	61	40	208	186–188	193
8	3.9	150	2,000	118	43	200–212	177–189	189–195

The number of control and exposure sessions conducted and the ranges of mean exposure levels for BLU, TYH, and OLY were combined. Exposure values are based on only those sessions with ten air gun impulses. SPL, sound pressure level; rms, root-mean-square; SEL, sound exposure level

For behavioral hearing tests, the subjects “whistled” in response to audible hearing test tones and remained quiet otherwise. Tone amplitudes were adjusted from one trial to the next using an adaptive staircase procedure. Hearing thresholds were based on the average tone level of at least five hit-miss or miss-hit reversal points and could generally be estimated within 2–4 min/frequency tested. AEP hearing tests utilized the single (TYH and OLY) and multiple (BLU) auditory steady-state response technique (Finneran et al. 2007), where sinusoidal amplitude-modulated tones were presented using a descending method of limits, and the evoked responses at the modulation rates were tracked to estimate thresholds at individual tone frequencies. AEPs were typically measured before and after the behavioral tests that surrounded the exposures (or mock exposures).

3 TTS Results

BLU participated in a total of 46 exposure sessions and 45 control sessions; TYH participated in 57 exposure sessions and 125 control sessions; and OLY participated in 45 exposure and 122 control sessions. The maximum exposure for all three subjects was ten impulses at a distance of 3.9 m from the air gun operating at 2,000 psi with a volume of 150 in.^{3} (the maximum output configuration for the air gun with the dolphin at the shortest practical distance). The mean cumulative SELs for the 150-in.^{3}, 2,000 psi, and 3.9-m exposure conditions were 195, 194, and 189 dB re 1 μPa^2·s (for ten impulses) for BLU, TYH, and OLY, respectively. The lower cumulative SEL for OLY was a result of his movement pattern during the exposure sequence.

No substantial TTS was observed in any subject at any test frequency during psychophysical testing compared with that measured during control sessions for any combinations of range, air gun volume, or air gun pressure. There were no systematic differences between the control and exposure data; any meaningful TTS would have been identifiable as an exponential increase of TTS with increasing exposure level. The relatively small mean values for TTS, similarity between the control and exposure data, and the poor correlation between exposure level and mean TTS all indicate that the air gun exposures did not result in any measurable TTS when using psychophysical (behavioral) hearing test methods.

The electrophysiological measurements were inconclusive. Pre- and postexposure AEP hearing tests were conducted before and after the behavioral hearing tests at levels 4–6 and 8 for BLU and at levels 7 and 8 for TYH and OLY. No measurable TTS was seen in BLU or OLY; however, TYH's electrophysiological data did show a small TTS (9 dB) after exposure to ten impulses from the air gun at the 150-in.^{3}, 1,500 psi, and 3.9-m range condition (193 dB re 1 μPa^2·s cumulative SEL). Exposure at a higher level produced a smaller TTS (6 dB). Standard deviations about these mean values were high (10 and 7 dB, respectively). It is unusual that the mean TTS actually decreased from level 7 to level 8; however, the exposure SEL increased only 1 dB between these conditions and TYH's anticipatory behavior may have affected the resulting TTS.

The results of this study contrast with previous TTS testing with a seismic water gun, where (behavioral) TTS was observed in a beluga after an exposure with SEL of 186 dB re 1 μPa^2·s. The differences between the auditory and behavioral effects of the water gun and air gun may have been a result of the relatively low-frequency content of air gun impulses compared with the relatively high-frequency hearing ability of dolphins or the lower peak-to-peak pressures produced by the air gun.

4 Behavioral Reactions

We did not observe significant behavioral reactions in BLU after exposure to any of the air gun impulses; however, behavioral reactions were observed in both TYH and OLY at the maximum exposure level. Both subjects appeared to anticipate the next exposure in a sequence and may have been attempting to mitigate the effects of the impulses. It is not known to what extent this anticipatory behavior during the highest exposures affected the TTS results (i.e., whether they were able to mitigate the effects of the exposure).

5 Conclusions

TTS measurements can be safely conducted with dolphins exposed to various combinations of air gun volume and pressure and at various distances, and if the exposure levels are gradually increased, dolphins may show little reaction to the air gun impulses, even at ranges as close as 3.9 m and with the air gun operating at 150 in.^{3} and 2,000 psi. Exposures of up to ten impulses from a 150-in.^{3} air gun operating at

2,000 psi (cumulative SEL of 189–195 dB re 1 $\mu Pa^2 \cdot s$) did not produce a clear, reliable TTS in any of the three dolphins; this may be a result of the relatively low-frequency content of the air gun impulses compared with the dolphin's range of best hearing or the lower peak-to-peak SPL compared with earlier impulsive sources.

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Chapter 123
Communicating the Issue of Underwater Noise Pollution: The *Deaf as a Fish* Project

Linda Sebastianutto, Michael Stocker, and Marta Picciulin

Abstract Aquatic noise pollution is largely ignored by the lay public. How experts communicate this issue is critical to move public opinion. In 2010, the Cassa di Risparmio di Gorizia (CaRiGO) bank sponsored the *Deaf as a Fish* project that included local underwater noise monitoring, a boat census, a pamphlet for nonexperts, and some seminars and public meetings. This project allowed us to raise interest in this issue. Using accurate and understandable language in a light-humored setting goes far toward cultivating trust from a public audience that can be intimidated or suspicious of complicated scientific messaging.

Keywords Underwater noise • Communication • Lay public

1 Introduction

Since the 1960s, the increase in human activities along coastlines worldwide and in the sea has caused an commensurate increase in the underwater noise levels, especially in the low-frequency range (<500 Hz) where noise produced by many anthropogenic activities is concentrated, with physiological, behavioral, and population effects on marine animals (Slabbekoorn et al. 2010). Even though the issue of aquatic noise pollution is of increasing interest in the scientific community and among territorial managers and legislators, this problem is largely ignored by the lay public, which rarely recognizes this form of pollution or considers it as important as other forms of acute pollution (e.g., chemical pollution).

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For this reason, moving public opinion is extremely important to advance consensus and awareness of the issue and promote the best practices for noise mitigation in the sea. To achieve this goal, experts must find the correct way to communicate and sensitize the issue to the broader public outside typical institutional settings (e.g., schools and science museums; Bush-Gibson and Rinfret 2010).

The *Deaf as a Fish* project was sponsored in 2010 by the Cassa di Risparmio di Gorizia (CaRiGO), a local Italian bank. It aimed to make people aware of ocean noise pollution with different kinds of activities including monitoring the local coastal underwater noise and a census of the boats, the production of a pamphlet for nonexperts with the basics of marine bioacoustics, and some good practices to prevent underwater noise pollution in everyday life. The pamphlet was sent to many scientific libraries, marine museums, and institutions around Italy and several seminars and meetings for the general public were commissioned.

Here we describe the different phases of the project and discuss the reaction of the public.

2 The Project

2.1 Noise Monitoring

Study Area

The two sites chosen for the acoustic survey are in a semienclosed basin, limited in size (20 × 20 km) and particularly in depth (24 m), in the Gulf of Trieste, a shallow bay of the Adriatic Sea in the extreme northern part of the Mediterranean Sea. It is part of the Gulf of Venice and is shared by Italy, Slovenia, and Croatia (Malačič and Petelin 2001). The sites are representative of two extreme noise conditions: a busy port and a nature reserve.

The Port of Monfalcone is the most northern port in the Adriatic Sea. It covers an area of 680,000 m^2 and over 4.5 million tons of various goods are handled there each year. The port specializes in general cargo and dry bulk cargo, with a focus in specific commodities. Depth ranges from −9.5 to −11.7 m and the access canal is 4,500 m long, 11.70 m deep, and 166 m wide (http://www.porto.monfalcone.gorizia.it/porto.htm).

The Valle Cavanata Nature Reserve is a 327-ha protected wetland of international value by the Ramsar Convention, which is an international treaty signed in 1971 for the conservation and sustainable utilization of wetlands. Situated in the easternmost part of the Grado Lagoon in Grado, Italy, during the 1920s, it was embanked, provided with adjustable floodgates, and transformed into a brackish area for fish farming. The fish-farming activities were maintained until 1995, after which the management of the water levels was reconfigured to favor the bird fauna. A complete list of the spotted or resident species of interest at the reserve is available at www.regione.fvg.it/rafvg/export/sites/default/RAFVG/ambiente-territorio/tutela-ambiente-gestione-risorse-naturali/allegati/Pdg_Val_Cavanata_All_A_completo_x_approv.pdf.

Noise Recordings and Boat Census

One of the aims of *Deaf as a Fish* was to describe the local underwater soundscape in two representative areas in the province of Gorizia at two extreme levels of anthropogenic impact. We did a 2-years acoustic survey in the two areas. Recordings were made at the same time at the two locations, only with good sea and weather conditions. To better compare the two soundscapes and describe their short- and long-term temporal variations, we analyzed the sound pressure levels (SPLs) of the broadband, low-frequency band (<2,500 Hz) where fish hearing occurs and the majority of anthropogenic noise is concentrated (Greene and Moore 1995) and the high-frequency band (>8,000 Hz) that corresponds to the hearing range of odontocetes because bottlenose dolphins are seldom spotted in the area (Francese et al. 2007; Genov et al. 2009). For more details on the acoustic recordings and analyses, see Picciulin et al. (2013). Because of the lack of prior local data, the noise levels and the spectra at the two locations were compared with the environmental sound levels measured in different areas characterized by a high level of ship traffic (Wenz 1962; Urick 1983). In addition, we compared the recorded sound levels with the audiograms of some local species of naturalistic and economic interest [sea bass (Lovell 2003), Mediterranean damselfish (Wysocki et al. 2009), and bottlenose dolphin (Brill et al. 2001)] and evaluated a possible impact on their hearing abilities. Along with noise recordings, we did a census of the boats passing near the recording points, noting the distance, type of boat, size, type of engine, and velocity.

2.2 *The Pamphlet*

We wrote the first pamphlet in Italy on underwater noise pollution for nonexperts: *Deaf as a Fish: Tackling Underwater Noise Pollution*. Using an easy and light-humored approach with graphics and a lot of comic characters, we explained the basics of marine bioacoustics, what marine species can hear, how they produce sounds, and what are the effects of man-made noise on them and suggested some good practices to prevent underwater noise pollution in everyday life. The pamphlet was translated for the US public with the help of Michael Stocker of Ocean Conservation Research, Lagunitas, CA. This pamphlet was sent to scientific libraries, marine museums, and institutions all around Italy and was distributed during the seminars (Fig. 123.1).

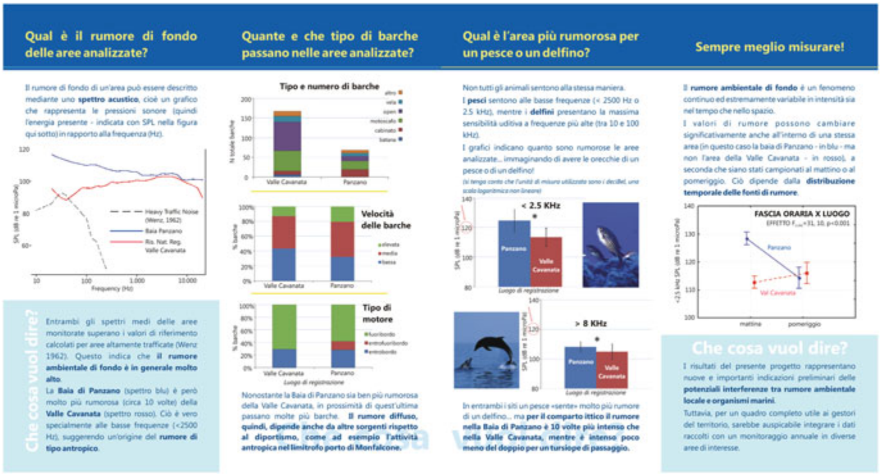
2.3 *Meetings and Seminars*

With the support of the University of Trieste and the WWF-Miramare Natural Marine Reserve, we organized a series of seminars in schools and different yacht clubs in the region because we strongly believe that apart from the institutional

Fig. 123.1 Front cover of the *Deaf as a Fish* pamphlet

stakeholders, it is extremely important to engage as many people as possible, including yachtsmen and fishermen, because leisure boating is the major source of boat traffic in the area and therefore the major source of underwater noise.

We presented a PowerPoint program introducing the different sound sources of underwater noise (nonbiological, biological, and anthropogenic sources) and the different functions of sound for marine animals. To introduce the concept that not all species hear the same frequencies, we proposed a "game." We played the sound of a speedboat engine, saying that this was what humans hear, then band-pass filtered the same noise and played it back, asking people to pretend to have other species' ears: low frequency for fish and invertebrates and high frequency for marine mammals. This was an effective way to make people aware of the diverse hearing abilities of animal species. After this critical stage, we introduced the description of the detrimental effects of underwater noise, making some comparisons between noise levels that can harm humans in air and the corresponding level in the marine environment. We also presented the results of the acoustic survey and the possible impacts of the recorded noises on local species so that the research provided direct and immediate information to managers and other stakeholders (Fig. 123.2). Each meeting concluded with an open discussion session.



Qual è il rumore di fondo delle aree analizzate?

Il rumore di fondo di un'area può essere descritto mediante uno **spettro acustico**, cioè un grafico che rappresenta le pressioni sonore (quindi l'energia presente - indicata con SPL nella figura qui sotto) in rapporto alla frequenza (Hz).

Che cosa vuol dire?

Entrambi gli spettri medi delle aree monitorate superano i valori di riferimento calcolati per aree altamente trafficate (Wenz 1962). Questo indica che **il rumore ambientale di fondo è in generale molto alto**.

La **Baia di Panzano** (spettro blu) è però molto più rumorosa (circa 10 volte) della **Valle Cavanata** (spettro rosso). Ciò è vero specialmente alle basse frequenze (<2500 Hz), suggerendo un'origine del **rumore di tipo antropico**.

Quante e che tipo di barche passano nelle aree analizzate?

Nonostante la Baia di Panzano sia ben più rumorosa della Valle Cavanata, in prossimità di quest'ultima passano molte più barche. **Il rumore diffuso, quindi, dipende anche da altre sorgenti rispetto al diportismo, come ad esempio l'attività antropica nel limitrofo porto di Monfalcone.**

Qual è l'area più rumorosa per un pesce o un delfino?

Non tutti gli animali sentono alla stessa maniera.

I **pesci** sentono alle basse frequenze (< 2500 Hz o 2.5 kHz), mentre i **delfini** presentano la massima sensibilità uditiva a frequenze più alte (tra 10 e 100 kHz).

I grafici indicano quanto sono rumorose le aree analizzate... immaginando di avere le orecchie di un pesce o di un delfino!

(si tenga conto che l'unità di misura utilizzata sono i decibel, una scala logaritmica non lineare)

In entrambi i siti un pesce «sente» molto più rumore di un delfino... ma **per il comparto ittico il rumore nella Baia di Panzano è 10 volte più intenso che nella Valle Cavanata, mentre è intenso poco meno del doppio per un tursiope di passaggio.**

Sempre meglio misurare!

Il **rumore ambientale di fondo** è un fenomeno continuo ed estremamente variabile in intensità sia nel tempo che nello spazio.

I valori di rumore possono cambiare significativamente anche all'interno di una stessa area (in questo caso la baia di Panzano - in blu - ma non l'area della Valle Cavanata - in rosso), a seconda che siano stati campionati al mattino o al pomeriggio. Ciò dipende dalla **distribuzione temporale delle fonti di rumore**.

Che cosa vuol dire?

I risultati del presente progetto rappresentano nuove e importanti indicazioni preliminari delle **potenziali interferenze tra rumore ambientale locale e organismi marini**.

Tuttavia, per un quadro completo utile ai gestori del territorio, sarebbe auspicabile integrare i dati raccolti con un monitoraggio annuale in diverse aree di interesse.

Fig. 123.2 Flyer with the summary of the results of the noise survey. It was distributed to the public during the seminars

3 Results and Discussion

The preliminary results showed that SPLs at both sites were very high, although the area next to Monfalcone Port was ten times noisier than that next to the Valle Cavanata Natural Reserve. This is not surprising considering that the Gulf of Trieste is a highly populated area, chronically exposed to acoustic pollution caused mainly by leisure boating during the tourist season and by commercial boat activities from the ports of Monfalcone and Trieste during the entire year. In general, because the amount of anthropogenic noise is higher in the low-frequency range, fish were potentially more negatively impacted by the noise conditions than were marine mammals swimming in the same area. In addition, even if the noise levels were higher near the port, the number of boats was much higher in the Valle Cavanata region. This shows that recreational boating was one of the most common activities, especially during the tourist season. However, the noise produced by different types of boats varied and depended on several factors such as type of engine, velocity, and size.

Having a good acoustic environment for species living within a particular area is an important factor for many biological activities that rely on acoustic communication (e.g., foraging, reproduction, territoriality, navigation). We speak about acoustic pollution when the recorded noise levels are so high that they create a kind of "acoustic fog" that masks propagation and reception of biologically relevant signals (Codarin et al. 2009). As a consequence, the fitness-related activities are impaired and the marine animals cannot achieve a useful sense of their surrounding environment (Sebastianutto et al. 2011). For this reason, it is important to promote noise monitoring to provide local institutions with information for better coastal management.

At the same time, it is important to identify and target some local species of natural and economic importance to evaluate the effects of noise pollution. During our meetings, we provided the preliminary results of the possible impacts of the noise levels on some local fish and marine mammal species. Discussing this topic had a twofold aim: scientists can show that their research activity provides immediate and useful data available to everyone and the public can understand the direct impact of underwater noise on animals that were familiar and dear to them.

As far as we know, the *Deaf as a Fish* project was the first Italian effort to sensitize people to this issue. The project had some resonance and was described in a local (*Il Piccolo*) and in a national (*La Repubblica*) newspaper. Moreover, one of the authors, Marta Picciulin, was interviewed on a national radio station. Especially after the publication of the *La Repubblica* article, the news was discussed on Web sites and blogs. The reactions were different, ranging from strong skepticism to great interest. In particular, during the seminars, we realized that the idea of the sea as a silent world is still deep seated; people are quite familiar with the idea that marine mammals produce and use sounds but are completely naive to the fact that fish and invertebrates also use sound in their lives. The common belief is that fishes are "mute" and people are very surprised when they discover that this is not the case. Some people, especially yachtsmen and fishermen, believe that our take-home message is to forbid or limit activities such as boating and fishing. For this reason, during educational activities such as *Deaf as a Fish*, it is important to reach not only an already interested public (e.g., students or environmentalists) but also people who are skeptical or suspicious of scientists. We stressed that human activities and environmental protection can coexist if people are aware of the consequences and, when possible, adopt some easy good practices to limit the impact. At the end of each seminar, people were allowed to ask questions, and often we observed a shift from a negative to a positive attitude. Using succinct, accurate, and understandable language in a light-humored setting goes far toward cultivating trust from a public audience that can be intimidated or even suspicious of more complicated scientific messaging.

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Chapter 124

Mapping Underwater Sound in the Dutch Part of the North Sea

H. Özkan Sertlek, Geert Aarts, Sophie Brasseur, Hans Slabbekoorn, Carel ten Cate, Alexander M. von Benda-Beckmann, and Michael A. Ainslie

Abstract The European Union requires member states to achieve or maintain good environmental status for their marine territorial waters and explicitly mentions potentially adverse effects of underwater sound. In this study, we focused on producing maps of underwater sound from various natural and anthropogenic origins in the Dutch North Sea. The source properties and sound propagation are simulated by mathematical methods. These maps could be used to assess and predict large-scale effects on behavior and distribution of underwater marine life and therefore become a valuable tool in assessing and managing the impact of underwater sound on marine life.

Keywords Good environmental status • Shipping noise

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1 Introduction

The investigations on the impact of anthropogenic and natural sound on marine life require the collaboration of different disciplines such as ecologists, behavioral biologists, and acousticians. The regulations in the United States (Marine Mammal Protection Act [MMPA] 1972; Endangered Species Act 1973) and the European Union (EU) aim to protect and preserve the marine environment. The EU's Marine Strategy Framework Directive (MSFD; European Commission 2010b) requires member states (MS) to achieve or maintain good environmental status (GES) by 2020. Specifically, the wording of Descriptor 11 requires "underwater noise to be at levels that do not adversely affect the marine environment." The MSFD further requires monitoring of "trends in the ambient noise within the 1/3-octave bands of 63 and 125 Hz (center frequency)" (European Commission 2010a).

In this study, the procedure for generating the sound maps relevant to the assessment of GES in the North Sea is discussed. It takes into account the intensity and frequency properties of sound from anthropogenic (e.g., shipping, underwater explosions, seismic surveys, pile driving) or natural (e.g., wind, rain) sources. The propagation loss (PL) is calculated analytically by taking into account sediment properties, bathymetry, and volume absorption (Weston 1976). Then the source and propagation models were used to produce annually or seasonally averaged sound maps for different frequencies and receiver depths for each different sound source. Hearing sensitivities of the different marine mammal and fish species determines the frequency range, and resolution of the available distribution data of the target species determines the required spatial and temporal resolution of these maps. Sound maps are presented for different natural and anthropogenic sources, including surface ships, underwater explosions, and wind. When such maps are linked with data on the distribution of marine mammals and fish, they can be used to assess the population-level impact of sound on the distribution of these organisms. The end product could become a valuable tool in improving the assessments of the impact of underwater sound on marine life.

2 Sources and Propagation

To generate sound maps, detailed input is required for the sound sources and propagation characteristics. The anthropogenic (ships, air guns, and pile driving) and natural sound (wind, rain, and lightning) source properties can be modeled by mathematical or empirical approaches (Ainslie 2010). Which technique is most appropriate depends on the characteristics of the source, and this can be described using either model. Each source model may require different approximations and metrics. Source level (SL) or energy source level (SL_E) can be used to describe the sound source characteristics. These are the source factor (S) and energy source factor (S_E), respectively, expressed as levels in decibels,

$$\mathrm{SL} = 10\log_{10}\frac{\mathrm{S}}{\mathrm{P}_{\mathrm{ref}}^{2} r_{\mathrm{ref}}^{2}} \quad \left(\mathrm{dB\,re\,1\,\mu Pa^2 m^2}\right)$$

$$\mathrm{SL_E} = 10\log_{10}\frac{\mathrm{S_E}}{\mathrm{P}_{\mathrm{ref}}^{2} r_{\mathrm{ref}}^{2} t_{\mathrm{ref}}} \quad \left(\mathrm{dB\,re\,1\,\mu Pa^2 m^2 s}\right)$$

where $\mathrm{P}_{\mathrm{ref}}$ is the reference pressure in water of 1 μPa, t_{ref} is reference time, and r_{ref} is reference range. For example, ships generate continuous sound that can be described with a SL. At larger distances, the ship can be treated as a point source that has an average SL (Wales and Heitmeyer 2002). On the other hand, underwater explosions and air guns are transient sources that are better described by their $\mathrm{SL_E}$. $\mathrm{SL_E}$ for the underwater explosions can be modeled by empirical approximations (Ainslie 2010). Air guns are commonly used in an array in seismic surveys. Calculation of the air gun signature requires more sophisticated methods that take into account the bubble motion, gas pressure, mass transfer, and optimization models (MacGillivray 2006).

Radiated total energy can give insight into the possible impact of the sources on marine life. The order of magnitude estimate of total “free-field energy” for the different types of sound sources is shown by Ainslie et al. (2009). The free-field energy of a sound source (or set of sources) is the total energy that would exist in the sound field due to that source (or sources) if placed in free space and operated with the same SL as the real source (or sources). This concept is useful for ranking disparate sources in terms of their potential for impact (Ainslie and Dekeling 2011) (Table 124.1).

To investigate the distribution of energy in the various locations, the accurate modeling of PL plays an important role in the sound mapping. PL for the continuous sources can be defined as

$$\mathrm{PL} = \mathrm{SL} - \mathrm{SPL}\left(\mathrm{dB\,re\,1\,m^2}\right)$$

where SPL is sound pressure level. For a transient source, PL takes the following form

$$\mathrm{PL} = \mathrm{SL_E} - \mathrm{SEL}\left(\mathrm{dB\,re\,1\,m^2}\right)$$

Table 124.1 Total (free-field) energy from the different types of anthropogenic sound sources in the North Sea

Type of source	Order of magnitude estimate of total (free-field) energy (kJ)
Air gun arrays	8,000
Shipping	3,000
Pile driving	700
Explosions	500

where SEL is sound exposure level. The underwater acoustic PL depends on the frequency and environmental properties such as sediment type, bathymetry, and sound speed profile. PL also depends on the receiver and source depths. To estimate PL, methods in either the frequency or time domains can be used. For continuous sounds such as ships, frequency domain methods are sometimes preferred. However, each method can have a different validity range depending on the frequency and environmental conditions. Thus a single method for the estimation of PL may not be sufficient for the entire frequency band. In the current study, Weston (1976) approaches are used to calculate average intensity. This approximation leads to good agreement with the outcome of other well-known propagation software (Sertlek and Ainslie 2013). For transient sources, time domain methods are required to capture the time dispersion of the signal that alters its shape and duration when it propagates in shallow water. Estimation of the time dispersion is important for choosing an appropriate averaging time window for determining the SPL (Sertlek et al. 2012).

By combining source and propagation models, sound maps are obtained. Maps of sound due to shipping, explosions, and wind are generated for the North Sea at different depths. In Fig. 124.1, annually averaged sound maps are shown for the ships and underwater explosions at 125 Hz. These sound maps are generated at 1 m below the sea surface.

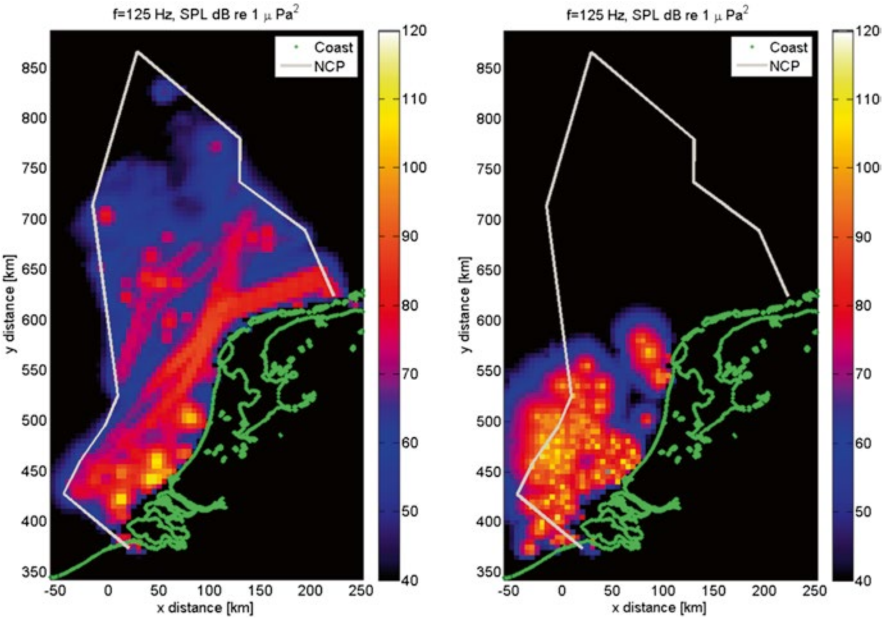

Fig. 124.1 Sound maps for shipping (*left*) and underwater explosions (*right*) at 125 Hz. *SPL* sound pressure level, *NCP* North Sea Caspian pattern, *f* frequency

To generate sound maps of shipping, data on vessel density in the North Sea Caspian pattern (NCP) area of the North Sea in 2010 were used. For the explosion maps, data from underwater explosions in 2010 and 2011 were used. The SL_E of explosions was calculated by an analytical approach (Ainslie 2010). Maps of wind noise can be obtained by using wind speed data from Royal Netherlands Meteorological Institute (KNMI) databases. The spatial distribution of marine mammals and fish in the North Sea can differ for each month or season. Also, they can spend different amounts of time at different depths. For this reason, monthly noise maps can be generated at the different receiver depths for a wide frequency range. For the broadband sound maps, PL between each source and receiver can be separately calculated at the center frequencies of 1/3-octave band.

3 Conclusions

Sound maps can provide insight into the sound distribution in general and the contribution of each source in particular. These maps can be used to assess the impact of anthropogenic sound by combining the maps with data on species distribution and their hearing sensitivity. This can be used to better understand the spatial use of the different species and predict, even in areas and periods where distribution data are not available, how the animals could react if anthropogenic underwater sound would be produced. Depending on the obtained result, new regulations for seismic surveys, pile-driving activities, and shipping routes can be set. Future sound maps need to incorporate sound impact isoclines, spectral filtering by species-specific sensitivity curves, and sound metrics other than SPL (e.g., particle velocity, continuous or intermittent temporal variability). Estimation of the effects on marine animals and fish should account for the biological context, e.g., predator–prey interactions.

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Chapter 125
Passive Acoustic Monitoring of the Environmental Impact of Oil Exploration on Marine Mammals in the Gulf of Mexico

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Abstract The Gulf of Mexico is a region densely populated by marine mammals that must adapt to living in a highly active industrial environment. This paper presents a new approach to quantifying the anthropogenic impact on the marine mammal population. The results for sperm and beaked whales of a case study of regional population dynamics trends after the Deepwater Horizon oil spill, derived from passive acoustic-monitoring data gathered before and after the spill in the vicinity of the accident, are presented.

Keywords Sperm whales • Beaked whales • Oil spill • Marine mammal population • Noise

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1 Introduction

Deepwater ecosystem damage and recovery assessments are usually not the first priorities in the aftermath of heavy industrial operations and environmental disasters (for example, oil spills) because they do not immediately impact human health and well-being, plus the evaluation methodology presents difficult scientific challenges. As an example, of 239 projects submitted to the National Oceanic and Atmospheric Administration (NOAA) as potential Gulf of Mexico (GoM) restoration projects after the Deepwater Horizon (DWH) oil spill, only one proposes to study the deepwater environment through monitoring fish distributions by standard sonar methods. However, a precedent for the need for such monitoring was established earlier by observation of negative changes in the resident population of *Orcinus orca* (Alaskan killer whale) during the decade after the "Exxon Valdez" oil spill (Matkin et al. 2008). The observed response of the deepwater ecosystem to the Exxon Valdez oil spill showed a critical need to change the methods of assessing ecological impact. The immediate acute mortality response is an insufficient assessment factor because ecosystem exposure to a nonlethal dosage of toxins over long periods of time had negative effects on marine mammal population health over a 10-year period (Peterson et al. 2003). Advancement of ecosystem long-term monitoring methodology is required to understand and predict chronic, delayed, and indirect long-term risks and impacts.

Current assessment methods include point-to-point chemical and biological sampling and visual observations that require large human involvement and long and expensive ship cruises to collect information over extended areas. Several studies, initiated by NOAA, suggested a concept of marine sentinel organisms that can be used to gain understanding of potential threats to coastal environments and human health from anthropogenic ocean pollution (Bossart 2006). A change in marine mammal distribution and abundance caused by environmental stresses can have a major impact on the functioning of the whole deepwater ecosystem and, at the same time, reflects changes from epipelagic to bathypelagic ocean layers and provides insight into the ocean ecosystem health because mammals are consumers of production at many trophic layers (Bowen 1997; O'Hara and O'Shea 2005; Moore 2008). The advancement of our limited understanding of the marine mammal role in the ocean ecosystem has to come as an interdisciplinary effort combining acoustic, biological, chemical, and oceanographic data collections; mathematical modeling; and integrated analysis of various data types in searching for global patterns in distribution of species, pollutants, and human activities. Passive acoustics should play a key role in this effort because it provides information on the health of the deepwater ecosystem on different levels from observed abundance dynamics to prey distribution (Marques et al. 2009; Ackleh et al. 2012).

The emphasis of this study is on the first-year responses to the oil spill of resident deep-diving marine mammals (*Physeter macrocephalus* [sperm whales] and Ziphiidae [beaked whales]) that densely populate an area near the DWH incident site.

2 Experiments

The Littoral Acoustic Demonstration Center (LADC), composed of scientists from four Gulf State universities, was founded in 2001. One of its goals is to study the impact of human activities in the ocean on marine mammals, with an emphasis on the GoM region (Ioup et al. 2005, 2009; Tashmukhambetov et al. 2008; Sidorovskaia et al. 2011). Before the 2010 GoM oil spill, the LADC had conducted six passive acoustic surveys in the GoM, and by chance, in 2007, the LADC conducted a 2-weeks visual and acoustic survey of marine mammal activity just 15 and 40 km away from the DWH platform, giving it a unique prespill baseline dataset of marine mammal activity at the oil spill source. Earlier surveys had also been conducted at sites 80 km from the DWH location. In September 2010, the LADC returned to those same survey sites to repeat its underwater acoustic recordings, gathering data to support the first and perhaps the only comparisons of pre- and postspill estimates of the marine mammal population change.

The LADC uses an autonomous, battery-powered, full-ocean-depth acoustic-recording system (environmental acoustic recording system [EARS] buoy) that satisfies a US Navy data-collection requirement for continuous passive acoustic monitoring, recording for periods up to 2 years. The deployment design is site specific and for this application is optimized for detection, classification, and localization of marine mammals present in the area of interest. The hydrophone depth deployments in the 2007 and 2010 experiments targeted the feeding depths of deep-diving marine mammals broadly present in the northern GoM (endangered *Physeter macrocephalus* and Ziphiidae). The EARS buoys were developed and are maintained by the Naval Oceanographic Office (NAVOCEANO). The current EARS configuration allows detection and classification of vocally active marine mammals in the frequency range between 10 Hz and 96 kHz.

Figure 125.1 presents some data-collection sites used by the LADC between 2001 and 2010. In Fig. 125.1, the circles indicate three experimental sites used in 2001 and 2002. The first experimental locations were chosen for their high concentrations of visually observed endangered *Physeter macrocephalus*, as reported by NOAA. These sites are ~80 km away from the DWH platform (Fig. 125.1, fire symbol). Squares indicate the northern and southern locations of the EARS buoys in the 2007 experiment that are ~15 and 40 km, respectively, from the DWH location. The 2007 locations were chosen for the relatively high density of visual observations of GoM beaked whales. Three EARS buoys were deployed in a triangular configuration at each 2007 location for enhancing tracking capabilities. The 2007 data are rich in beaked whale recordings and are the first beaked whale recordings in the GoM. In September 2010 (the fifth month after the oil spill beginning), three pairs of the LADC EARS buoys were redeployed, one pair at each previous location (Fig. 125.1, red pins) 15, 40, and 80 km away from the DWH site. Recording hydrophone depths were ~1 km at the northern and southern sites and 800 m at the shallower western site to target the foraging depths of *Physeter macrocephalus* and Ziphiidae. The EARS buoys continuously recorded acoustic data for 12 days each at a 192-kHz sampling rate. All buoys were successfully recovered during a following cruise in October 2010.

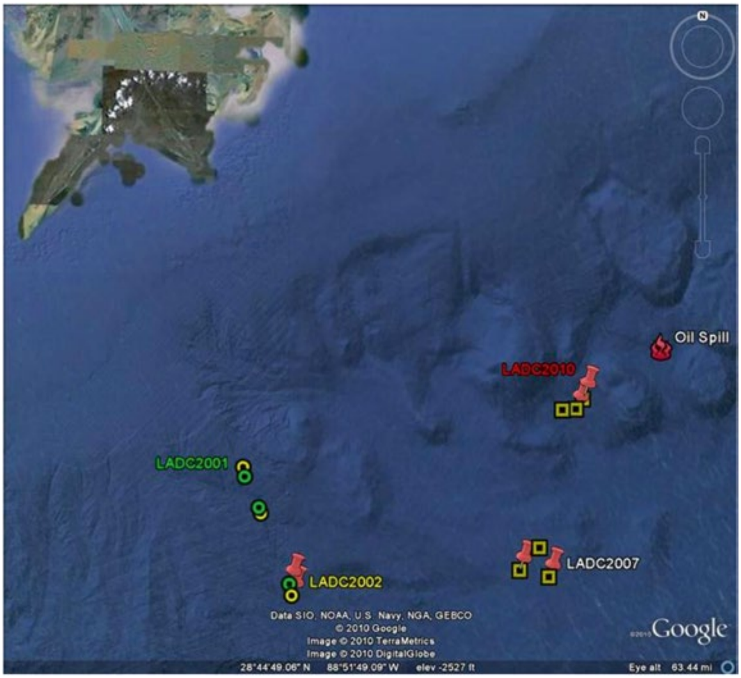

Fig. 125.1 Locations of the Littoral Acoustic Demonstration Center (LADC) experiment sites in 2001 (*green circles*), 2002 (*yellow circles*), 2007 (*yellow squares*), and 2010 (*red pins*). A fire symbol denotes the Deepwater Horizon (DWH) incident site (28°44′12″ N, 88°23′14″ W). Yellow squares indicate the northern and southern locations of the environmental acoustic recording system (EARS) buoys in 2007 that are ~15 and 40 km, respectively, away from the DWH platform. These maps were produced using GoogleEarth. Reproduced from Ackleh et al. (2012) with permission from the Journal of the Acoustical Society of America

3 Data Processing and Interpretation

The data-processing workflow consists of two main components: (1) detecting and counting acoustic signals (echolocation clicks) of a particular species and (2) inserting acoustic cue counting results into a statistical model to estimate species average regional abundance based on their acoustic activity during the experiment.

Clicks from different marine mammal species were classified by comparing the energy distribution in three bands: low (L) band (3–20 kHz; *Physeter macrocephalus*), medium (M) band (25–55 kHz; Ziphiidae), and high (H) band (60–90 kHz; Dephinidae [dolphin] family). A click-detection event was defined as any point where the band energy over a 2.7-ms window exceeded a threshold of 10 standard deviations above the mean over a 10-min averaging interval. The click-detection process was applied to all three frequency bands. When searching for *Physeter macrocephalus* clicks, a click event must be present in the low band only; concurrent detection in medium- or high-frequency bands disqualifies it as a *Physeter macrocephalus* click (but may qualify it as another species such as a Dephinidae family click).

A population estimate based on detected acoustic cue count is given by Marques et al. (2009) and Ackleh et al. (2012)

$$\hat{D} = \frac{n_c(1-c)}{\pi\omega^2 P(Tr)} \tag{1}$$

where n_c is the number of detected cues over a time period (T), c denotes an estimated proportion of false positive detection, and r is an estimated cue production rate by a single mammal (i.e., expected number of cues per unit time). Then Tr is the total number of cues expected to be produced by an animal over time period T, and $n = n_c(1-c)/(Tr)$ is an estimated number of animals producing clicks during time T. A target region is considered as a circular area (a) centered at the buoy location with the maximum detection radius of ω; thus, $a = \pi\omega^2$. The probability of detecting a given animal through a sample of size n from a population of size N is given by $P = n / N$. A suitable estimate of P in passive acoustic-detection studies when an animal can be identified by a cue only (no concurrent tagging) is discussed in detail in Ackleh et al. (2012). Therefore, P represents the estimated probability of detecting a cue in current experimental conditions. A bootstrap technique was used for estimating the variance of $\hat{D}$ (Ackleh et al. 2012).

To date, we have assessed changes in regional populations of *Physeter macrocephalus* (Ackleh et al. 2012) and Ziphiidae at sites that are 15 and 40 km away from the oil spill location by processing data and comparing the results from the 2007 and 2010 experiments. In these estimations, the following parameters were used for calculating abundance using (1). The proportion of false positive detections (c) was obtained from the comparison of manual and automatic detections and is equal to 0.059 for *Physeter macrocephalus* in both 2007 and 2010 and 0.22 in 2010 and 0.46 in 2007 for Ziphiidae. Cue production rate per second per whale (r) and detection range (ω) are taken from the literature and are primarily based on data from tagged animals. These parameters are equal to $r = 1.44$ clicks/s and $\omega = 20\,\text{km}$ for *Physeter macrocephalus* and $r = 2.5$ clicks/s and $\omega = 4\,\text{km}$ for Ziphiidae (Watwood et al. 2006; Zimmer et al. 2008).

The final results are presented in Fig. 125.2. Analysis and comparison of the 2007 and 2010 *Physeter macrocephalus* regional population estimates (Fig. 125.2a) show that a decrease in the number of *Physeter macrocephalus* at the site nearest to the DWH (15 km away) exceeds statistical uncertainties and can be accepted as an existing trend (Sidorovskaia et al. 2011; Ackleh et al. 2012). The 40-km away site displays a moderate increase in the population of *Physeter macrocephalus* in 2010 after the spill. We conjecture that sperm whales prefer feeding grounds further away from the spill site. The Ziphiidae family exhibits a completely different response (Fig. 125.2b). The number of animals at the 15-km away site is considerably higher in 2010 than in 2007. An increase in Ziphiidae numbers at the 40-km site is also clearly observed. A similar statement, that Ziphiidae returned to the spill site proximity right after the active spill was closed, was also made by John Hildebrand of Scripps Institution of Oceanography in a presentation at the Marine Mammal Commission meeting (New Orleans, May 2011). One of the plausible explanations is that Ziphiidae return to their feeding grounds due to availability of prey for this

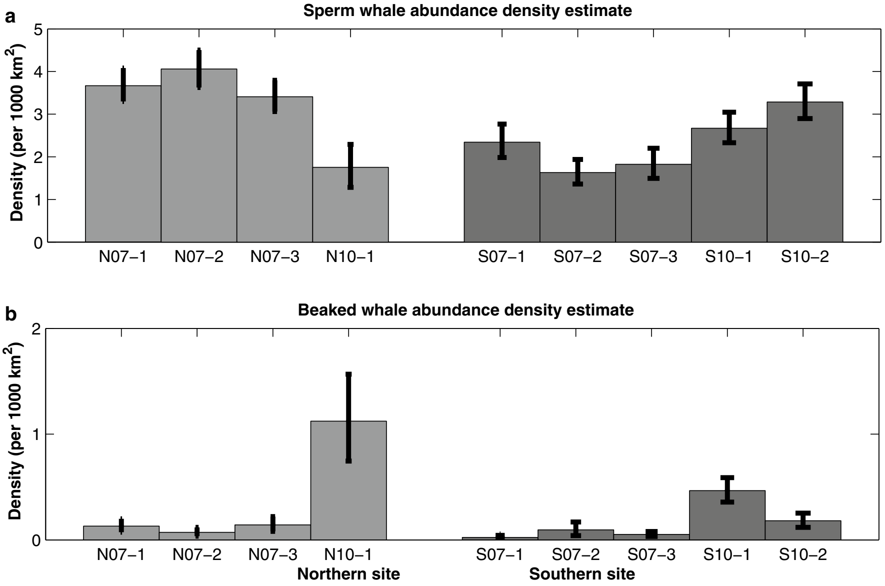

Fig. 125.2 The 95% confidence interval of the average hourly density for the 15-km (*light gray*) and 40-km (*dark gray*) away locations. N07-1, N07-2, N07-3, S07-1, S07-2, and S07-3 are data for 2007. N10-1, S10-1, and S10-2 are data for 2010. (**a**) *Physeter macrocephalus*; (**b**) Ziphiidae. Modified from Ackleh et al. (2012) with permission from the Journal of the Acoustical Society of America

family of marine mammals. It has been brought to our attention by David Bates of the Naval Oceanographic Office (private communication, 24 October 2012) that international fishing fleets, usually fishing in the area for squid, were required to stop fishing operations and leave the area affected by the oil spill. Squid are a source of Ziphiidae food, so replenished food sources due to interrupted commercial fishing operations may be a reason for the higher concentration of animals in the area. Also, during the 2007 data collection, a seismic exploration survey and a remotely operated vehicle were operating in the vicinity. This may have contributed to the decreased activity of Ziphiidae in the area. There is very little information about the distribution, abundance, and seasonal migration of Ziphiidae in the GoM. Additional observational data and research are critical to understanding their response.

4 Future Research

With the establishment of a critical baseline of population assessment data, the LADC is uniquely positioned to initiate consistent long-term acoustic monitoring in the northern GoM and to provide long-term assessment of the impact of environmental stresses on the abundance of at least three families of GoM marine mammals (*Physeter macrocephalus*, Ziphiidae, and Delphinidae).

The LADC acoustic datasets also contain a wealth of information about the environmental state of the GoM concurrent with marine mammal recordings, such as noise levels due to oil exploration/production activities and passing storms, density of food calls emitted by animals before consuming prey, and composition of stock (gender, size) due to variations in emitted signals. We plan to extract other relevant environmental information from the acoustic data and to correlate these new data with observed abundance trends. Inferring secondary information from prespill and postspill recordings may allow the discrimination of oil spill effects on an abundance from other environmental factors that can cause temporal migration away from an observational area.

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Chapter 126
BIAS: A Regional Management of Underwater Sound in the Baltic Sea

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Abstract Management of the impact of underwater sound is an emerging concern worldwide. Several countries are in the process of implementing regulatory legislations. In Europe, the Marine Strategy Framework Directive was launched in 2008. This framework addresses noise impacts and the recommendation is to deal with it on a regional level. The Baltic Sea is a semienclosed area with nine states bordering the sea. The number of ships is one of the highest in Europe. Furthermore, the number of ships is estimated to double by 2030. Undoubtedly, due to the unbound character of noise, an efficient management of sound in the Baltic Sea must be done on a regional scale. In line with the European Union directive, the Baltic Sea Information on the Acoustic Soundscape (BIAS) project was established to implement Descriptor 11 of the Marine Strategy Framework Directive in the Baltic Sea region. BIAS will

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develop tools, standards, and methodologies that will allow for cross-border handling of data and results, measure sound in 40 locations for 1 year, establish a seasonal soundscape map by combining measured sound with advanced three-dimensional modeling, and, finally, establish standards for measuring continuous sound. Results from the first phase of BIAS are presented here, with an emphasis on standards and soundscape mapping as well as the challenges related to regional handling.

Keywords Marine strategy framework directive • Management • Acoustic noise • Soundscape • Acoustic standards

1 Introduction

The Marine Strategy Framework Directive (MSFD; Directive 2008/56/EC) was launched in July 2008. It treats 11 pressures that potentially have a negative effect on the marine environment, and among these is Descriptor 11 that deals with underwater noise. It is a qualitative descriptor that states that "Introduction of energy, including underwater noise, is at levels that do not adversely affect the marine environment." It consists of two indicators where the first indicator addresses the distribution of loud low- and midfrequency impulsive sounds and the second deals with continuous low-frequency sound. To harmonize the implementation, the European Union established the Technical Subgroup on Underwater Noise (TSG-Noise) that has published two reports in which they have given guidelines for the descriptor and general recommendations on issues related to its implementation (van der Graaf et al. 2012; Dekeling et al. 2013). In these reports, the group proposes the

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establishment of a noise registry for bookkeeping of the impulsive noise events. It gives interpretations on how to choose thresholds and addresses issues with the scale. Finally, it gives guidance on a monitoring program. The aim of the MSFD is to achieve good environmental status (GES) by adhering to the thresholds of the indicators. In case of Descriptor 11, these are not established. It is therefore important to evaluate these indicators together, with a critical eye. Should all countries employ the same thresholds? Should a regional area establish a common grid for the spatial scale of the registry? How will member states share data? How to define GES by establishing a trend? Some of these questions were dealt with by the TSG-Noise group during 2013 and 2014. Irrespectively of their agenda, the member states were forced to implement the Descriptor and especially to have an operational monitoring system in place in mid-2014. It should be underlined that Article 6 in the Directive states that the Descriptors should preferably be dealt with on a regional level. For these reasons, the Baltic Sea Information on the Acoustic Soundscape (BIAS) project was established.

2 The BIAS Project

The BIAS project was started in September 2012, financed by the EU LIFE+ program; Sweden, Finland, Estonia, Poland, Germany, and Denmark are partners in the project. The project has five objectives: (1) to raise awareness of underwater sound in the region, (2) to implement Descriptor 11 on a regional level, (3) to assess the soundscape of the Baltic Sea by combining measurement and modeling, (4) to develop planning tools that can be used regionally, and (5) to establish regional standards and methodologies that will allow for cross-border handling of data and results.

The monitoring program will be performed by adhering to the standards that will be established in the project. Similarly, the data will be analyzed using standardized signal-processing routines. Results will be subjected to quality control and finally stored in a common data-sharing platform.

3 The Baltic Sea

The Baltic Sea is a semienclosed sea bordered by nine states. It consists of eight subcatchment areas (subbasins) and a number of harbors. The number of ships is one of the highest in Europe. It is estimated that ~2,000 sizeable ships are at sea at any time. Furthermore, several large ocean-based wind farms are planned to be erected in the Baltic Sea, which may add additional noise to the marine environment. The majority of the large ships pass the Öresund area (the Sound) or the Belt area on their way to major harbors in the Baltic Sea. The number of ships has been estimated to double by 2030 (WWF 2010), which undoubtedly will increase the pressure on the marine environment. The Baltic Sea differs from other European areas, e.g., it has an average depth of ~55 m, several large archipelagos, permanent salinity stratification at ~90 m depth, and a complex sediment structure. Furthermore, during the summer, a thermocline develops in the surface layer. From an acoustical point of view, the Baltic Sea is a shallow-water body and thus challenging. During the summer, a sound channel is present in the upper surface, which gives rise to an extended propagation distance. Isoveli is the prevailing situation in winter, which gives rise to shorter propagations distances. Thus, winter and summer have to be treated separately. Even if the acoustical situation is complex, a joint management of underwater sound requires common methodologies. One way to proceed is to employ standards.

4 Standards for Measuring Underwater Sound

For a comparison of results, it is vital to adhere to accepted standards. There are several attempts going on worldwide. The Netherlands, Germany, and the United Kingdom agreed on a terminology (Ainslie 2011). The American National Standards Institute (ANSI)/Acoustical Society of America (ASA) released a report (2009) that treats methodology for establishing ship signatures. The TC8 SC2 Joint Working Group of the International Organization for Standardization (ISO) is currently working on measurement standards of ships in deep water. Furthermore, the TC43 SC3 group deals with underwater acoustic terminology. However, these initiatives will not treat ambient noise, except for the terminology. Due to the present void, the BIAS project is developing standards/protocols for the measurement of ambient noise. The standards/protocols will treat the handling of sensors, handling of data, specification of sensor systems, and signal processing. The standards/protocols will include both definitions and check like lists for users to guide in the handling of sensors and data. Adhering to the standards will ensure that measurement, handling, and analysis, irrespective of user and sensor, are conducted in a standardized way. The standards/protocols will be used in the monitoring program and in the analysis of data.

5 Measurements

The focus of the first phase of the BIAS project is on measurements. One year after the start of the project, 40 sensors will be deployed in the Baltic Sea. The measurement period covers a full year and the sensors will be surfaced every third month and subsequently redeployed. There are a number of challenges related to deployments, for example, the northern and eastern regions that are covered by ice in winter and the shallowness of the Baltic Sea in combination with heavy fishing that results in a high risk to loose sensors.

Sensor positions have to be both “representative” from an acoustic point of view and chosen to minimize the risk of sensor loss. A scheme is presented here that makes use of the ship densities and special considerations. The aim is to find a representative position of the sensors, representative in the sense that the locally measured sound should characterize the trend of a larger area with significant accuracy. There are several factors that will come into play when choosing the positions, such as shipping density, convergence/divergence of shipping lanes, depths, fishing activities, and areas of special interest. A starting point in the decision process is to make use of available information related to sound activities. Here, three consecutive steps are presented. In the first step, the annual ship passages (shipping density) at prespecified sections are established. In the second step, special areas are included, and in the final step, special considerations are made.

The annual density maps of shipping (including AIS and vessel monitoring system [VMS] data) are essential for the final positions. First, the shipping lanes, which will constitute candidates for the final sensor positions, are identified. An example is shown in Fig. 126.1 where the ship transects (not including fishing vessels) are shown for the Baltic Sea.

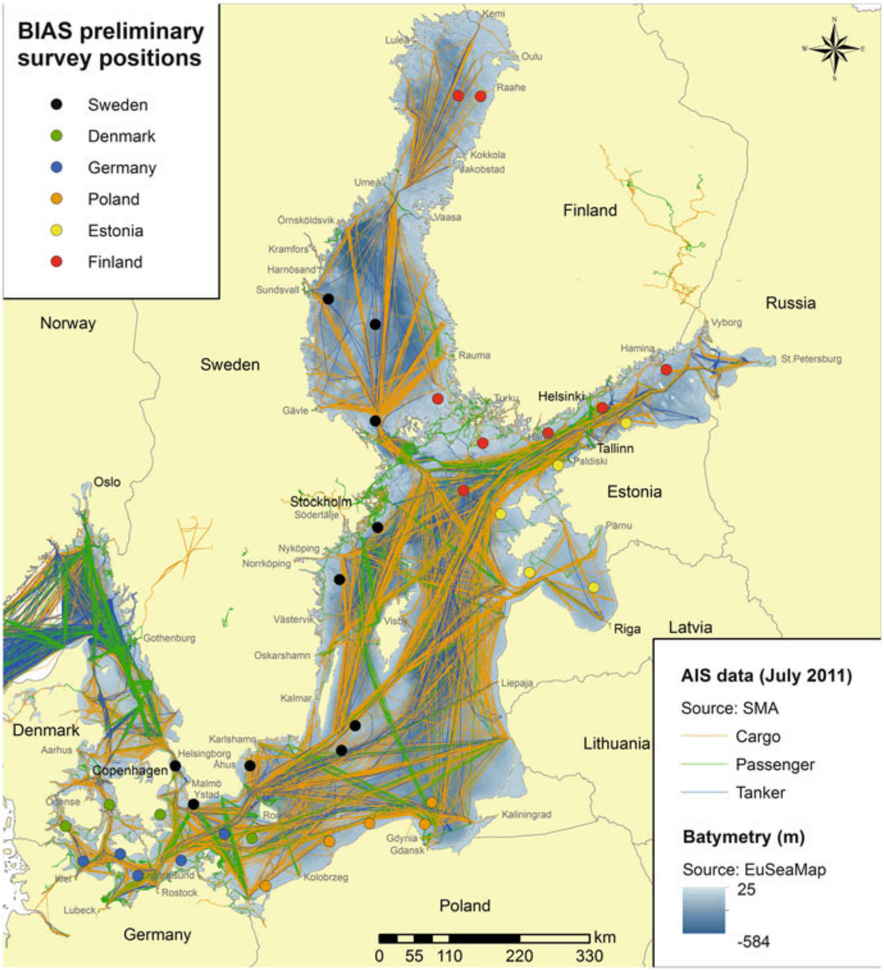

Fig. 126.1 Ship traffic in July 2011 at the major transects in the Baltic Sea. *Color of the lines* indicates type of ship. *Colored dots* show the planned deployment positions

It should be stressed that the density can change due to shipping lanes diverging or converging. The second step is to sort the lanes in density (passage) order, thereby obtaining a ranking list. A final sorting is done by dividing the shipping densities in the list into quartiles. The 25% quartile (Q1) of low shipping density is classified as minor shipping lanes. The shipping lanes falling above the 75% quartile (Q3) are classified as heavy shipping lanes and the rest as medium shipping lanes.

Depending on the number of deployed sensors, special areas may be included in the observational program. Marine reserves, Nature 2000 areas, dedicated areas with little or no industrial activity, and "potential silent areas" are examples of special areas. The final decision of their inclusion in the observational program depends on the number of sensors and the importance of the areas. When the final positions are established, special concern should be given to the nearby area of the positions. Information on fishing activities might be used to avoid a loss of sensors due to unwanted trawling events, which are normally done at low speeds (<6 kn). By establishing the trawling activities in the region, for example, by using VMS data, the areas to be avoided can be identified. If necessary, the position can be adjusted to an area with lower fishing frequency, thereby minimizing the probability of loss due to trawling (see Fig. 126.1). If feasible, the final position can be adjusted to a position nearby a shipwreck, which normally is avoided by fishers. Some of the acoustic sensors will be located in areas where stationary oceanographic monitoring systems (or other structures) are located. Care has to be taken, however, to avoid that the platform-generated noise does not adversely affect the performance of the acoustic sensors. It should be underlined that sediment properties (related to attenuation of sound) in an area can vary on a relatively short spatial scale as well as the vertical properties (sound profile). If possible, the final position should be on a location where the sediment and depth are representative for the area. The final BIAS project positions are shown in Fig. 126.1. The close vicinity to the Sea of Åland deployment is shown in Fig. 126.2. It should be noted that the fishing activities are restricted to certain areas.

6 Modeling

One of the aims of the BIAS project is to produce soundscape maps of the Baltic Sea. There are several reasons for making soundscape maps. First, they give valuable information on the spatial distribution. Second, they extend measured values to the whole sea. Third, they can be used to interpret the obtained results. This will also be valuable in year-to-year comparisons where, for example, a slight shift of a traffic lane will appear as an increase or decrease in sound levels. Finally, the modeling will be used for reducing the number of sensors. It cannot be assumed that the managing authorities will continue this extended observational program after the BIAS project ends. By then, using model results, the minimum required number of sensors and their positions will be established.

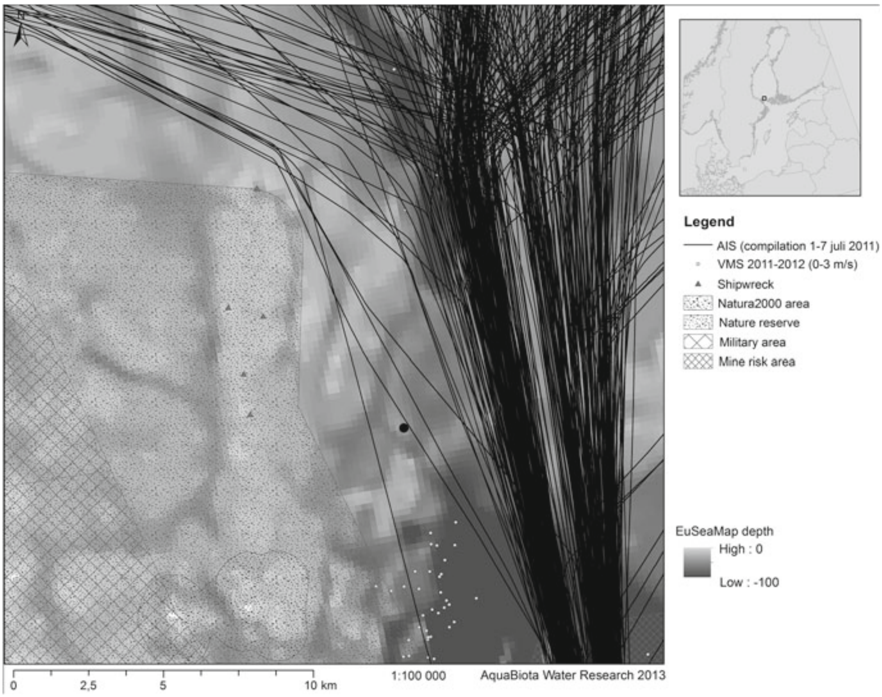

Fig. 126.2 Underwater acoustic measurements in the Sea of Åland in July 2011. Chart shows ship traffic as *black lines*. *White dots* show position of the fishing vessels (speed <6 kn). *Large black dot* is position of the acoustic sensor and triangles show ship wrecks

7 Quality Assurance

To ensure that the data and results are intercomparable and reliable, a quality-control system will be developed where quality assurance (QA) protocols will play a central role. This activity is closely related to the standards where guidelines are given on the handling of sensors, handling of data, and signal processing. By following the standards, the quality will be met, which the QA protocol will certify. An important aspect is to facilitate the reanalysis of data. The TSG-Noise group recommends that sound pressure levels and sound exposure levels be established. However, they do not rigorously define these quantities. Furthermore, we have to foresee that in the future new acoustic quantities will be of interest. It is, therefore, likely that a reanalysis has to be done. A too often occurring situation is that data cannot be reused due to lack of essential information, such as filter thresholds, tapering function, or even sampling rate. The QA protocols will ensure that full knowledge exist on sensors, data handling, and data processing and thus will allow for reanalysis of old data. The second reason for implementing QA protocols is to make cross-border comparison possible.

Underwater sound is likely to affect regions that are divided between different countries. Management of sound will, by its nature, involve several countries and it will be necessary to cooperate in managing the activity or the area. Here, an important requirement is that data are comparable. It is important to avoid situations when the same sea area is classified differently according to the noise level of neighboring countries.

8 End Products

To efficiently manage underwater sound in the Baltic Sea on a regional level, a number of tools will be developed. In the BIAS project, a regional registry will be established to handle impulsive noise according to the TSG-Noise group's recommendations. The BIAS project recommendation is to use International Council for the Exploration of the Sea (ICES) rectangles for spatial area for the Baltic Sea. This has the advantage that sound, fish, and mammals are dealt with on the same grid. A stock increase or decrease can thereby be correlated. To avoid double bookkeeping, a protocol will be used that uniquely identifies a sound event in the registry. A geographic information system (GIS)-based planning tool will be developed both for keeping track of the trend and for the soundscape map. This tool will be interactive and have a graphical user interface (GUI) that presents the prevailing sound situation. The tool will further be able to supply the present noise levels and the measure/modeled trend of a specific location. It will thus be possible to use the tool not only for now casting but also for forecasting. This feature is essential when traffic lanes are to be moved or when new offshore infrastructures are planned that will add noise to an already noisy environment.

9 Challenges

Establishing standards is not a task for an individual project but for an international organization. Still, the BIAS project has to be a forerunner due to the tight time plan that was decided by the European Commission. Even if the standards will be used internally, the BIAS project will deliver a recommendation of standards to the Baltic Sea member states at the project end. Establishing standards is a rather tedious and cumbersome process that aims for both consensus and acceptance. Thus, the BIAS project standards should be regarded as an interim solution that can be used as a starting point for an international group.

The aim to store data in a common data-sharing platform has shown to be unrealistic. Several of the Baltic Sea states have shown concerns in publishing acoustic data or even to share data between member states due to security reasons. The consequence is that the storing of data as well as the analysis will be done on a national level. This status makes a regional reanalysis problematic because it will require a request to several countries that might be turned down due to lack of financing or time. This also highlights the importance of using standards. The data and processing techniques of other countries will have to fulfill a comparable set of standards, especially when the reanalysis is done.

Finally, there are as many opinions on "tools" as there are managers. To compile sometimes conflicting demands will be a challenge. We will hopefully be able to report on the outcome in a future paper.

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Chapter 127
Psychoacoustic Studies of Spotted (*Phoca largha*) and Ringed (*Pusa hispida*) Seals

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Abstract Human development of the marine environment raises questions regarding the potential adverse effects of anthropogenic noise on marine mammals. For species that live in remote Arctic regions, recent and expanding human intrusions may pose a particular threat. Northern seals are poorly studied relative to their temperate counterparts and little is known of their acoustic ecology or behavior. Given this scarcity of relevant data, studies of hearing in Arctic seals are essential to characterize their auditory capabilities and to inform management decisions. This paper describes ongoing psychoacoustic studies that are examining aspects of hearing in two ice seal species.

Keywords Seals • Amphibious • Hearing • Noise • Arctic

1 Introduction

In recent years, rising anthropogenic noise levels throughout many of the world's oceans have become a cause for concern. Low-frequency noise associated with shipping and industrial activities has dramatically increased in certain areas (Huntington 2009; Moore et al. 2012). In the Arctic in particular, what was once a relatively undisturbed ecosystem is increasingly influenced by industrialization, which is enabled by the rapid melting of sea ice due to climate change. Among the many effects associated

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with elevated background noise levels in marine environments is the potential for auditory masking of relevant sounds. Because sound waves travel much farther than light under water, sound is available as a biologically significant stimulus in the oceans. For many species of marine mammals, including Arctic seals, hearing is likely to be a key sensory channel. Whether a seal is passively listening to gain information about the environment or actively communicating with a conspecific using vocalizations, the ability to perceive auditory signals may be hindered by the addition of noise. An understanding of the implications of specific sound-generating activities must therefore be informed by quantitative measurements of hearing.

Despite the apparent importance of hearing for many of their life history events, little is currently known about the auditory capabilities of most Arctic seals. Some hearing data do exist for pagophilic seals: auditory thresholds have been measured for *Pusa hispida* (ringed seals) and *Pagophilus groenlandicus* (harp seals) above 1 kHz (Terhune and Ronald 1971, 1972, 1975a, b), but the extent to which these data may be extrapolated to other northern seals is unclear. Furthermore, audiometric data are not available for any ice seal at low frequencies (<1 kHz), where most of the energy from industrial sounds such as shipping and seismic operations is concentrated. More extensive data are available for the temperate-living *Phoca vitulina* (harbor seal; Møhl 1968; Terhune 1988, 1991; Kastak and Schusterman 1998; Wolski et al. 2003; Southall et al. 2005; Kastelein et al. 2009; Reichmuth et al. 2013), but these data may or may not be relevant to an examination of noise effects on Arctic seals. To learn more about the acoustic ecology of ice seals and to determine their vulnerability to anthropogenic noise, it is important that the hearing sensitivity of additional ice seal species be measured across the entire frequency range of hearing. The work described here is part of an effort to obtain a comprehensive set of auditory measurements that will enable comparisons within and across species. Ultimately, the goal of this ongoing project is to fully describe the auditory capabilities of ice-living seals.

2 Measurements of Absolute Hearing Sensitivity

Psychophysical measurements of absolute hearing sensitivity provide valuable information about the range of audible frequencies and the peak sensitivity of the auditory system. For the purposes of comparative study, whether related to function, anatomy, or evolution, absolute (unmasked) auditory threshold measurements are essential (see Nummela and Thewissen 2008). In terms of conservation efforts, these unmasked data are relevant for understanding the perceptual abilities and vulnerability of a species to noise exposures. Because the acoustic scene is altered by the addition of anthropogenic noise into the environment, scientists and regulators must consider how Arctic seals, which rely on auditory cues to orient in their marine environment, may be affected by a changing sound landscape.

2.1 Underwater Hearing

In this study, measurements of underwater hearing were made in quiet conditions in two well-trained *Phoca largha* (spotted seals) and two ringed seals across the frequency range of hearing. Standard psychophysical methods were used, with an emphasis on environmental controls and a thorough characterization of ambient-noise conditions during testing (see Sills et al. 2014). Peak sensitivity for the spotted seals was ~51 dB re 1 μPa at 25.6 kHz, with a broad range of good auditory sensitivity extending seven octaves (Sills et al. 2014). Similarly, the best sensitivity for the ringed seals was ~51 dB re 1 μPa near 25.6 kHz (Sills et al. 2014). Audiograms for both species exhibited a characteristic mammalian "U-shape," with a sharp decrease in sensitivity near the high-frequency hearing limit and a more gradual low-frequency roll-off. When comparing within species, thresholds were remarkably similar between subjects throughout most of their hearing range. These auditory data indicate substantially better sensitivity than previously reported for ringed and harp seals (Terhune and Ronald 1972, 1975a).

Taken together, the new underwater hearing measurements obtained for spotted and ringed seals along with existing audiograms for related species support the notion that northern seals may form a functional hearing group (although more data are required to confirm this hypothesis). Underwater hearing capabilities appear to be similar across the *Phocini* tribe, at the very least for harbor, spotted, and ringed seals. Because psychophysical data are often difficult and expensive to obtain, the ability to reliably extrapolate hearing data across northern seals would be significant, especially for those tasked with sorting out regulatory issues involving vulnerable ice-living seals and human-generated environmental noise.

2.2 Aerial Hearing

Due to the amphibious nature of seals, a study of absolute aerial hearing sensitivity was also conducted. In-air thresholds for the two spotted seals indicated extremely acute hearing sensitivity: <10 dB re 20 μPa across the range of best hearing (from ~0.60 to 10 kHz), with a peak measured sensitivity of −13 dB re 20 μPa at 3.2 kHz (Sills et al. 2014). These data show hearing capabilities rivaling those of the best terrestrial carnivores including cats, dogs, and ferrets (Heffner 1983; Heffner and Heffner 1985; Kelly et al. 1986). Audiometric testing for ringed seals is ongoing in our laboratory, but data collected thus far suggest that the hearing of the two species is similar. Such sensitive aerial hearing may support the acoustic vigilance of these seals when hauled out or resting on ice floes or rocky substrates, especially during vulnerable periods such as the breeding and molting seasons.

3 Measurements of Hearing in the Presence of Noise

In addition to absolute measures of sensitivity, it is important to quantify the influence of noise on hearing. Among the many possible effects is the potential for increasing noise levels to interfere with the detection of biologically relevant sounds. The very low aerial thresholds measured in this study demonstrate that the hearing of these seals may typically be limited by environmental noise rather than the sensitivity of the auditory system. An understanding of auditory masking may thus be even more relevant to applied conservation questions concerning noise pollution than an understanding of absolute auditory capabilities.

Psychophysical studies of auditory masking often begin with the detection of pure-tone or narrowband stimuli in the presence of spectrally flattened “white” noise, and the resulting critical ratio data describe the ability of the auditory system to extract signals from within this noise background. More specifically, a critical ratio is calculated as the difference between the sound pressure level of the masked hearing threshold and the spectral density level of the masking noise at the test frequency (Fletcher 1940; Scharf 1970). This helpful metric provides insight into auditory processing capabilities and can also be used to estimate zones of auditory masking around a particular noise source in the environment, whether natural or anthropogenic.

In this psychoacoustic study, masked hearing thresholds were measured in the presence of octave-band noise in air and under water to determine the critical ratios. For the spotted seals, the critical ratios increased similarly in both media from ~13 to 28 dB between 0.100 and 25.6 kHz (Sills et al. 2014). There was close agreement between subjects and media. For the one ringed seal tested thus far, the critical ratios under water were comparable to those of the spotted seal subjects, increasing from 16 to 31 dB across the same frequency range (Sills et al. 2014). Previous masking studies in seals and sea lions have also shown relatively low critical ratios in pinnipeds, especially the seals. Our data widen the frequency range for which critical ratios are available for representative species. A comparative view supports the conclusion that at least the true seals are hearing generalists with respect to frequency processing, with enhanced abilities to detect signals in noise, indicated by their low critical ratios, across a range of frequencies. It has been suggested that this ability in seals is related to efficient sound detection in a noisy marine environment (Southall et al. 2000).

4 Summary

This ongoing hearing study provides insight into the perceptual abilities of ice seals under different acoustic conditions, informing best management practices for these species in an increasingly human-influenced Arctic environment. Spotted and ringed seals possess similar and very sensitive hearing capabilities across a wide range of frequencies. For at least the spotted seal, this acute sensitivity occurs both above and below the surface of the water and suggests a need for management of anthropogenic noise influences in both media.

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Chapter 128
A Seaway Acoustic Observatory in Action: The St. Lawrence Seaway

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Abstract A setup for measuring spectral source levels (SSLs) of ships transiting along a seaway, the traffic density and shipping noise, is presented. The results feed shipping-noise modeling that reproduces the actual in situ observations to map shipping-noise variability over space and time for investigating its effects on aquatic organisms. The ship's SSL databank allows sorting the different contributors to total shipping noise for assisting in exploring mitigation approaches (e.g., fleet composition, rerouting). Such an acoustic observatory was deployed since November 2012 for a complete annual cycle of measurements in the deep downstream part of the St. Lawrence Seaway.

Keywords Shipping noise • Ship source level • Shipping lane • Monitoring • North America

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1 Introduction

Shipping is the main anthropogenic contributor to ocean noise (Hildebrand 2009). The continuous increase in world shipping in the last decades is thought to be at the origin of the significant rise in low-frequency ocean noise in the northern hemisphere shipping belt (Andrew et al. 2002; McDonald et al. 2006, 2008; Hildebrand 2009; Chapman and Price 2011; Frisk 2012). The potential adverse effects of this growing underwater noise on marine life and ecosystems have attracted the attention of the scientific community, regulators, and the International Maritime Organization (Southall 2005; Wright 2008; Boyd et al. 2011; Leaper and Renilson 2012). Numerical modeling and software tools have been proposed to assist in the estimation of the shipping noise threat for marine organisms over the three-dimensional (3-D) volume and its temporal variability (e.g., Erbe and Farmer 2000; Frankel et al. 2002; Gisiner et al. 2006; Erbe et al. 2012). However, accurate and representative modeling of shipping noise requires appropriate inputs and a series of measurements of the actual in situ levels to compare with the simulated results. These latter data can be acquired for some *x-y-z* coordinates with hydrophones deployed in the environment (e.g., Simard et al. 2010; Gervaise et al. 2012; Merchant et al. 2012). Accurate and representative inputs to the models are, however, more difficult to gather, except for data on the propagation medium properties that can be obtained from ocean-monitoring programs.

With the widespread use of the automatic identification system (AIS) in world shipping, the location and identification of a large proportion of the noise sources to input to models in shipping areas are now possible (e.g., Erbe et al. 2012). The characteristics of the sources are, however, highly uncertain because of the large diversity of the ships comprising the fleet, their age and conditions, and the operation of their machinery. A bank of the actual spectral source levels (SSLs) of the ships sailing in the modeled environment is needed, including the quantification of the SSL dispersion by ship type, length, and speed. Such ship SSL data are generally nonexistent for nonmilitary or research vessels, although estimates are becoming available for some ship types and some areas (e.g., Erbe 2002; Wales and Heitmeyer 2002; Gervaise et al. 2012; McKenna et al. 2013). The building of such a databank for the large and diverse civil fleet remains to be done.

Because precise measurement of ship SSLs requires special setups and basin characteristics (American National Standards Institute [ANSI]/Acoustical Society of America [ASA] 2009), the conditions to build such a significant dataset to feed simulation models are rarely met along continental shelf seaways. Basins that are sufficiently large and deep enough to minimize the boundary effects on sound propagation (Jensen et al. 2011) are needed. Shipping lanes where ships transit at their regular speed along a narrow path and where the ship density is low enough to allow the isolation of single-ship acoustic signatures are also crucial. Waters where the extracted ship noise largely dominates the wind-generated noise are also desirable.

The downstream segment of the St. Lawrence Seaway in the Lower St. Lawrence Estuary in eastern Canada (Fig. 128.1a) meets all these requirements for gathering the desired significant merchant ship SSL dataset for representative shipping-noise modeling. This is feasible with a relatively simple mean, at low cost, by installing a

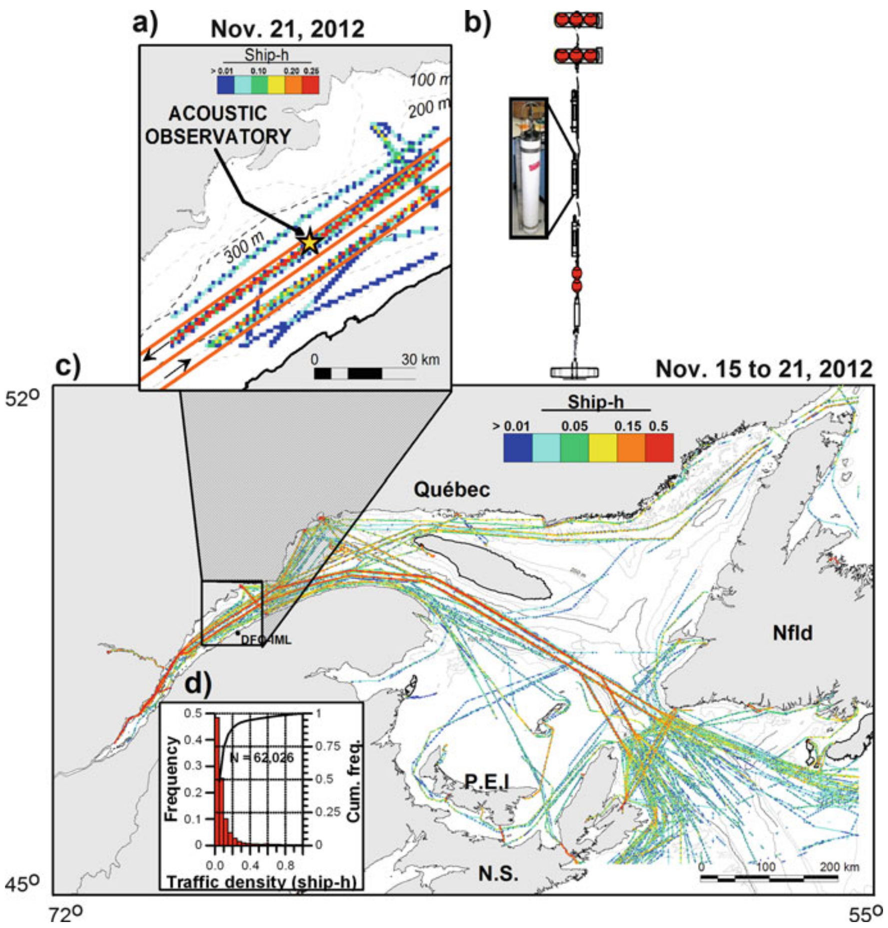

Fig. 128.1 (**a**) Location of the acoustic observatory and local traffic on 21 November 2012. (**b**) Sketch of the "I"-type mooring of the three AURAL hydrophones array. (**c**) One-week shipping traffic density in the St. Lawrence system from 15 to 21 November 2012. (**d**) Corresponding histogram. Cum. freq., cumulative frequency

dedicated acoustic observatory along the seaway. Besides, this area is a world-renowned feeding habitat of threatened blue whales (*Baleanoptera musculus*) and several other whales because of the regional oceanographic process of food aggregation (Simard and Lavoie 1999; Simard 2009) and comprises a marine protected area and a marine park dedicated to marine mammal conservation. Last, being just off the Maurice Lamontagne Institute of Fisheries and Oceans Canada, the area is ideally located for such research.

Here, we present the characteristics of the acoustic observatory we have recently installed for monitoring the St. Lawrence Seaway over a complete annual cycle and gather the information to feed models to map the shipping noise in blue and fin (*Balaenoptera physalus*) whale habitats in the St. Lawrence system. The observatory objectives are to get (1) the detailed description of the noise generated by the various ships transiting on this seaway, (2) the traffic diversity and density over space and time throughout the whole basin through the AIS data, and (3) the characteristics of the local ocean noise and its different contributors over the annual cycle.

2 Methods

The recommended shipping route in this 50-km-wide segment of the Lower St. Lawrence Estuary is the 20-km central strip of the U-shaped Laurentian Channel, which is 350 m deep in the area (Fig. 128.1). Two 10-km-wide lanes separate the upstream traffic on the north from the downstream traffic on the south. The observatory was installed in the middle of the upstream traffic lane.

2.1 AIS Data on Shipping Traffic

AIS data were acquired in raw binary format from the Department of Fisheries and Oceans (DFO) Canadian Coast Guard (CCG) monitoring network of shipping traffic in Canadian waters and converted to ASCII text format with a custom-made program. Besides time and position, AIS data fields retained for the observatory include the ship identifier (Maritime Mobile Service Identity), its type, length, breath, draft, speed over ground (SOG), and course direction. These latter fields will serve to build data filters to look for particular ship categories of interest for further analyses. The AIS covered all ships larger than 300 GT by shipping regulation and a large proportion of smaller ships and boats on a noncompulsory and utility basis; some small vessels that were not equipped with AISs were ignored. Their relative contribution to total underwater noise is, however, expected to be small.

The metric used to report traffic density for the total traffic or any ship category subset is ship-hour in a 1 square kilometer bin integrated over the time period of interest (e.g., hour, day, week, or month). One ship spending 0.5 h in a 1-km^2 bin would give 0.5 ship-h. Two ships spending 0.25 h in a 1-km^2 bin would also give 0.5 ship-h. AIS positions of ships are broadcast at varying rates, sometimes including gaps of several minutes. The trajectories were therefore interpolated to a common time resolution of 0.5 s for the analyses.

2.2 Acoustic Data on Ship SSLs, Shipping Noise, and Sound Speed Profile

The acoustic setup of the observatory followed as much as possible the ANSI recommendations for grade A to grade B standard measurement of ship SSLs from a beam aspect (ANSI/ASA 2009). However, adaptations were required because the

Table 128.1 Coordinates of the St. Lawrence Seaway acoustic observatory

Period	Latitude	Longitude	Bottom depth (m)	Hydrophone depth (m)		
				Top, 15°	Middle, 30°	Lower, 45°
1 November 2012–9 May 2013	48°51.820′ N	68°12.960′ W	345	71	NA	295
9 May 2013–30 October 2013	48°52.611′ N	68°11.074′ W	345	75	168	295

opportunistic measurement approach of the observatory, with no coordination with the ship's commandments, differed from the dedicated ship SSL measurements for which the ANSI standard were developed. These adaptations included especially larger tolerance windows for distances to the closest point of approach (CPA) and the related 3-D geometry of the SSL measurements.

The acoustic observatory consisted of a vertical array of three AURAL autonomous hydrophones (http://www.multi-electronique.com/pages/auralm2en.htm) mounted on an "I" mooring anchored on the bottom with two train wheels (Fig. 128.1b). An IXsea Oceano acoustic release (http://www.ixsea.com/en/products/18/oceano.html) and subsurface floats that maintained the 280-m-long mooring line in a vertical position completed the mooring gears (Fig. 128.1b). Special care has been taken to minimize noise that could originate from any components of the mooring by ensuring the absence of moving parts and metal-to-metal joints and by minimizing the drag with streamlined floats (cf. Simard and Roy 2008). The hydrophone depths were chosen in accordance with the ANSI recommended measurements of the beam aspect SSL at three slant angles of 15°, 30°, and 45° for a ship crossing the array at a CPA of ~300 m (Table 128.1). The AURAL hydrophones were equipped with HTI-96 min hydrophones, whose nominal receiving sensitivity (RS) is flat at −164 ± 1 dBV/μPa over the 0- to 16.4-kHz recording band based on measurements for a fleet of such hydrophones made at the Defense Research and Development Canada facility in Dartmouth, NS (Gervaise et al. 2012). The digitization rate was 16 bit and the hourly duty time was 60%, which resulted in 0.6 TB of acoustic data over 6 months of recordings for each hydrophone. Sound speed profiles were obtained from conductivity temperature and depth (CTD, SBE-19; http://www.seabird.com/products/profilers.htm) profiles made when servicing the observatory and from the DFO regional ocean-monitoring program (Galbraith et al. 2013).

2.3 Data Analysis

Ships in the upstream traffic lane that cross the observatory at CPAs that are within the acceptance window for measuring beam aspect SSLs, assuming propagation loss from a spherical spreading law (e.g., 0.3 to ~3 times bottom depth), are tagged as prospects for SSL estimation. Larger CPA ranges are possible with other propagation loss models, including experimentally derived models, up to a limit of ~3–5 km for keeping a high signal-to-noise ratio (SNR). Tagged ships are then accepted for SSL measurement if there is no other ship within a given radius (e.g., 5 km) around the observatory and their sailing SOG exceeds a given threshold (e.g., 2 km/h). When all the conditions are met, the third-octave broadside-centered ship SSL is estimated following the ANSI standard by linearly averaging received levels (RLs) at the hydrophones, corrected for ambient noise (if SNRs are <10 dB) and propagation loss, for the time window the ship is within a given horizontal angle range (e.g., ±30°) centered at the CPA. For CPAs > 3.0 × bottom depth, the time window is kept fixed at the value reached to keep the analyzed recordings to similar durations. The ambient-noise levels considered in the ANSI standard are those prevailing outside the measurement window extended by a given factor (e.g., 2 or 3). More robust estimates of ambient noise are considered as an alternative (e.g., Kinda et al. 2013). To comply with the ANSI standard, SSL third-octave bins with a SNR of <3 dB should be rejected. Similarly, data affected by occasional strum noise from mooring vibrations, which are often associated with springtide currents and a slight deepening of the top AURAL hydrophone (i.e., mooring tilt), are rejected.

The spectral and broadband levels over a series of bandwidths of total ocean noise RLs at the hydrophones were measured with a high-resolution time window (Gervaise et al. 2012). The time series for each hydrophone was then analyzed in combination with the ship ranges from AIS data. Various characteristics of the noise are then extracted to identify and sort out its different ambient (cf. Kinda et al. 2013), natural physical, biological, and anthropic components and to estimate the actual in situ propagation loss over the recorded frequency band.

3 Results

Examples of the observatory results are presented in Figs. 128.1 and 128.2. The shipping traffic per square kilometer mapped for 1 week in November 2012 showed that international traffic utilized the main track as well as the secondary regional and local shipping routes including the fishing paths, from AIS-tracked bottom trawlers (Fig. 128.1c). In the observatory area, traffic in the upstream direction was concentrated in the middle of the 10-km-wide shipping lane where the observatory was located (Fig. 128.1a). Over 1 week, 62,026 1-km^2 bins were visited by a ship. Cumulated traffic density per bin was, however, low everywhere (Fig. 128.1d), with only the main seaway along the Laurentian Channel, ferry lines, and port entrances having densities greater than 1 ship-h (i.e., 1-km^2 bin crossed by ~27 ships sailing at 15 kn; Fig. 128.1c).

The plot of the distance of the ships to the observatory for a single day displayed two ranges of CPAs centered at ~10 and ~1 km, which corresponded to the upstream and downstream lanes of the seaway (Fig. 128.2a). On 21 November 2012, 24 ships transited the seaway, 10 in the downstream lane and 14 in the upstream lane. Among these latter ships, five transited when the hydrophone array was not recording (Fig. 128.2a, shaded time periods). Therefore, their SSLs could not be estimated. Among the remaining nine upstream-going ships, seven transited within a CPA window of 0.1–1.5 km from the array but only five were not accompanied by other

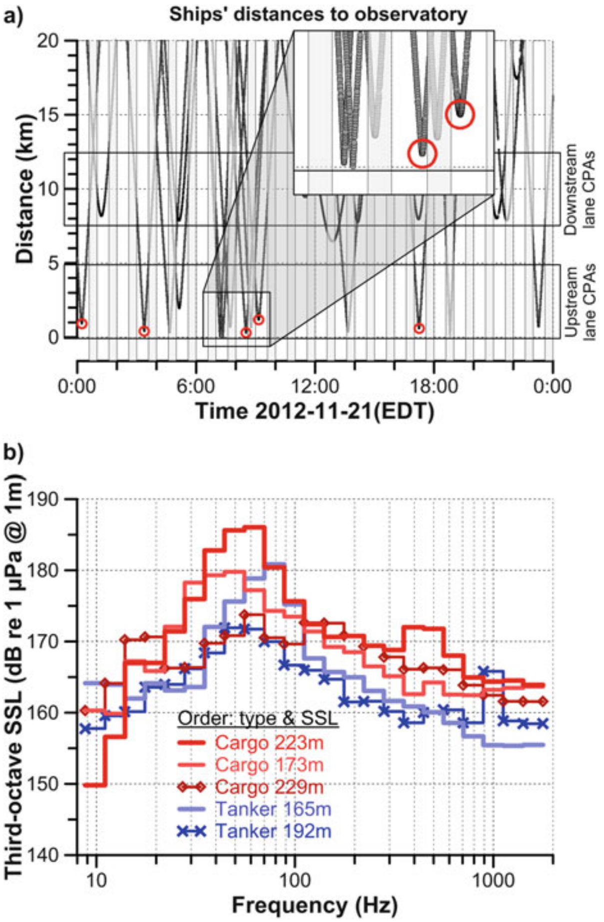

Fig. 128.2 (**a**) Ships' ranges to the observatory on 21 November 2012. Shaded bands indicate nonrecording periods. *Large red circles* are closest points of approach (CPAs) of five valid ships for spectral source level (SSL) estimation. (**b**) Third-octave SSL of the five valid ships

ships in a radius of 5 km (e.g., Fig. 128.2a, zoomed window) and conformed to the other selection criteria for SSL estimation (Fig. 128.2a, circled CPAs).

These five eligible ships were two tankers and three cargo ships, varying in length from 165 to 229 m (Fig. 128.2b). Their third-octave SSLs peaked at 172–187 dB re 1 µPa at 1 m between 50 and 90 Hz, and their overall spectral envelope from 10 Hz to 2 kHz was ~10 dB wide (Fig. 128.2b). Two ships had strong spectral rays between 300 and 1,000 Hz that were not smoothed out by integrating on third-octave bands. As expected, there was no clear relationship between the SSL and ship length (Fig. 128.2b). On the contrary, the smallest tanker had a 10-dB higher SSL peak than the 28-m longer one and the largest of the cargo ships had the lowest levels over a large part of the spectrum.

4 Discussion and Conclusions

This St. Lawrence Seaway acoustic observatory study presents an example of a relatively simple setup for mid- to long-term monitoring of a seaway and the associated radiated noise in the underwater environment by the transiting ships. Compared with other main seaways of the world, the relatively low local traffic and the particularities of the site, with its deep, wide, and sheltered basin, offer the exceptional advantages of allowing estimation of the spectral signatures of the ships comprising the fleet. The initial results presented here indicate that ~36% (5 of the 14 ships in the upstream daily traffic) of the ship SSLs of the fleet could be estimated this way, assuming that ships transiting in the downstream lane are the same ships returning to sea. By increasing the recording duty time of the hydrophone array to 100%, this fleet proportion is raised to 60%. Given that ~6,000 ship transits are counted in this part of the St. Lawrence Seaway annually, operating the observatory for 1 year with a 100% duty time would generate a bank of SSLs of the international merchant fleet comprising more than 1,500 ships (0.6 × [6,000 ships/2 lanes]).

The results clearly show that the actual SSLs of ships can hardly be estimated by the ships' overall characteristics such as length and tonnage and that there is a high variability among apparently similar ships that must be taken into account. By measuring the SSLs of a large number of diverse ships, it is hoped that better estimates, representative of real in situ mean SSLs and its error, can be computed by ship categories. This would help improve the accuracy of shipping-noise propagation models and take into account the inherent variability and diversity of the sources.

Besides the above evident outcomes of such a seaway acoustic observatory for characterizing ship SSLs of a fleet and analyzing the present local shipping noise, another interest for the measurements includes providing the data required to manipulate the fleet and traffic characteristics in simulated scenarios to assess the effects of future industrial projects or shipping-noise management measures on marine ecosystems. This is particularly relevant for the scenarios of the opening of new shipping routes in the Canadian Arctic and Subarctic in coming decades as a consequence of the present rapid warming of polar regions. The acquired observatory dataset could also be exploited for correlation studies of marine mammal calling behavior in relation to shipping noise or for monitoring the 3-D water mass structures from acoustic tomography techniques using the ships around the observatory as opportunistic sources.

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Chapter 129
Small-Boat Noise Impacts Natural Settlement Behavior of Coral Reef Fish Larvae

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Abstract After a pelagic larval phase, settlement-stage coral reef fish must locate a suitable reef habitat for juvenile life. Reef noise, produced by resident fish and invertebrates, provides an important cue for orientation and habitat selection during this process, which must often occur in environments impacted by anthropogenic noise. We adapted an established field-based protocol to test whether recorded boat noise influenced the settlement behavior of reef fish. Fewer fish settled to patch reefs broadcasting boat + reef noise compared with reef noise alone. This study suggests that boat noise, now a common feature of many reefs, can compromise critical settlement behavior of reef fishes.

Keywords Anthropogenic noise • Habitat selection • Patch reefs • Settlement stage

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1 Introduction

Hearing is one of the key sensory systems used by coral reef fishes for guiding orientation and habitat selection during the settlement phase when young individuals return from the plankton and enter into benthic reef habitats to begin juvenile life (Montgomery et al. 2006; Leis et al. 2011). At this time, the young of many of the principal families of reef fishes have been shown to be attracted by reef noise (Tolimieri et al. 2000; Leis et al. 2003; Simpson et al. 2004, 2005a), particularly at the higher frequency components (570–2,000 Hz) produced by invertebrates (Simpson et al. 2005a, 2008a).

Because reef noise is generated by resident fish and invertebrates, different reef and associated coastal habitats have distinct acoustic profiles (Radford et al. 2008, 2010; Kennedy et al. 2010; see Chapter 102 by Piercy et al.). Recent studies show that these different fingerprints of noise emanating from reefs and habitats could provide road maps to locate suitable environments both at settlement and during nocturnal migrations of juveniles (Simpson et al. 2008b). For example, settlement-stage *Haemulon flavolineatum* (French grunt) preferentially select noise from reefs over noise from mangrove and sea grass habitats (Huijbers et al. 2012) and a variety of reef species, including representatives of the Nemipteridae and Pomacentridae (two common and abundant families of reef fishes), are able to use noise to select preferred microhabitats when settling to reefs from the plankton (Radford et al. 2011).

The importance of reef noise as a cue for orientation raises an important question about the potential impacts of anthropogenic noise within these environments on the settlement process of reef fishes. Large human populations occur along the coasts of many tropical regions and, to date, studies of their effects on reef systems have generally focused on overfishing, eutrophication, sedimentation, and other stressors rather than the noise produced by fishing, transport, tourism, recreation, and industrial development (Slabbekoorn et al. 2010), yet these anthropogenic noise sources may present one of the most ubiquitous anthropogenic impacts in both coastal and oceanic environments. Noise pollution is known to affect behavior (Bruintjes and Radford 2013; Wale et al. 2013a), physiology (Wale et al. 2013b), communication (Vasconcelos et al. 2007; Codarin et al. 2009), sensory thresholds (Scholik and Yan 2002), and stress levels (Wysocki et al. 2006) of both aquatic vertebrate and invertebrates.

Recent studies of the effect of boat noise on reef fishes have produced inconsistent results; Jung and Swearer (2011) found that young temperate reef fishes were not deterred from entering traps by boat noise, whereas Holles et al. (2013) used auditory choice chambers to demonstrate a negative impact of boat noise on orientation of settlement-stage reef fish. Both studies provide only limited evidence of the effect of noise on young fish because they only examined one aspect of the settlement process (attraction/avoidance to sound in the former study and orientation in the latter). However, experimental protocols developed by Simpson et al. (2005a) provide a useful and simple means to explore directly the effects of boat noise on a larger part of the settlement process and offer the opportunity to gain a more comprehensive insight into the effect of sound on this aspect of the life history of coral reef fishes. This protocol involves the use of reefs constructed of natural material (live and dead corals) as settlement sites for young fish combined with the deployment of speakers broadcasting boat and reef noise. We used this approach to test the hypothesis that there would be a difference in levels of settlement of young fishes to reefs depending on whether sound systems moored above the reefs were broadcasting nocturnal recordings of the sounds of local reefs or tracks with boat noise overlaid on reef sounds. This experiment provides the first direct evidence of the effect of anthropogenic noise on the settlement process of coral reef fishes.

2 Methods

For eight nights (12–19 November 2012) centered on the new moon (14 November), we tested the effect of the playback of boat noise on the settlement of young reef fish in the shallow (2–5 m depth) back-reef habitat at Lizard Island Research Station, Great Barrier Reef (14°40.939′ S, 145°26.635′ E and 14°41.035′ S, 145°26.613′ E).

Recordings of five different boats, each a 5-m aluminum dinghy with a 30-hp 2-stroke Suzuki outboard moving 10–100 m from the recording station, were made from a kayak to avoid the sound of waves on the hull of the boat with a hydrophone 2 m below the surface in ~5-m-deep water over a sandy bottom and >100 m from reefs. The five nocturnal reef recordings (between 1,920 and 2,020 h) were made with the hydrophone 1 m directly above different natural reefs in water depths of 2–5 m. Reef and boat recordings and compilation tracks made from these recordings were all made using a calibrated omnidirectional HTI-96-MIN hydrophone (frequency response = 2 Hz to 30 kHz, voltage sensitivity = −165 dB re 1 V/μPa; High Tech, Inc., Gulfport, MS) and a Sony PCM-M10 24-Bit recorder (96 kHz sampling rate; Sony Corporation, Tokyo, Japan) that was also fully calibrated using pure sine wave signals, measured in-line with an oscilloscope, and produced by a function generator (TTi RS Components 216-069, TG230, 2 MHz Sweep/Function Generator). Recordings were analyzed using SASLab Pro v5.2.07 (Avisoft Bioacoustics, Berlin, Germany).

For the playback experiment, we used a similar protocol to that of Simpson et al. (2005a) in which a cluster of four 0.25-m^3 experimental patch reefs constructed of live and dead *Pocillopora damicornis* (cauliflower coral) collected locally were arranged 3 m apart in a square formation around a central mooring in 1–4 m depth (depending on tides) on extensive sand flats just offshore of the Research Station. We built two replicate setups 180 m apart and >100 from nearby reefs (Fig. 129.1a).

As young reef fishes settle to coral reef habitats during the night, we moored a sound system consisting of a battery (12 V 7.2 Ah sealed lead-acid), WAV/MP3 player (Philips GoGear VIBE, Koninklijke Philips N.V., Amsterdam, The Netherlands), and amplifier (M033N; 18 W; frequency response: 40–20,000 Hz; Kemo-Electronic GmbH, Langen, Germany) sealed in a watertight housing and attached to an underwater speaker (Lubell Labs University Sound UW-30, frequency

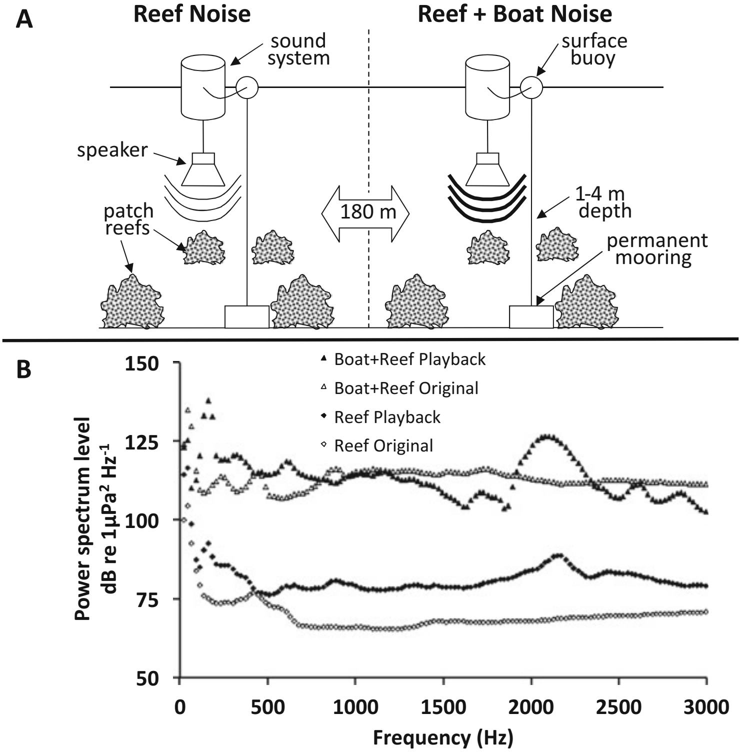

Fig. 129.1 (**a**) Experimental study system showing configuration of reefs and underwater sound playback equipment. (**b**) Averaged power spectra (fast Fourier transform length 4096, 23.4 Hz bandwidth, Hamming window) for acoustic pressure levels in medleys of five original reef (*diamonds*) and reef+boat (*triangles*) recordings (*open symbols*) compared with recordings next to the patch reefs of the same recordings being played back through underwater speakers (*solid symbols*)

response 100–10,000 Hz; University Sound, Columbus, OH) over each patch reef cluster at dusk, with one system playing a recording of one of five nearby coral reefs (each replicate randomly selected) on a continual loop through the night and the other system playing the same recording but with recordings of three of five different research station boats (each replicate randomly selected) overlaid on the same track. The allocation of reef or reef+boat treatments was randomized each night, which resulted in clusters one and two receiving reef+boat noise three and five times, respectively, over the eight nights.

Each morning before 08:00, the sound systems were retrieved and the patch reefs were cleared of newly settled fishes by divers using clove oil and hand nets. All fish were counted and identified.

Where frequency of occurrence was sufficient, the relative numbers of fish arriving on reefs near the speakers playing back reef noise with and without additional boat noise were compared using a Wilcoxon signed-rank test, which is a nonparametric paired analysis that does not require normal distributions of catches through the nights and can be used with small sample sizes ($n=8$ nights).

3 Results

The recorded noise level of the nocturnal reefs was 112.8±0.1 dB re 1 μPa (root mean square [rms]; 1 s averaging; mean±SE), whereas the level for boats driving around the hydrophone was 136.1±0.5 dB re 1 μPa. The playback levels for the reef and reef+boat recordings were determined iteratively to generate levels that were similar to those in the original recordings (reef=117.0±0.3 dB re 1 μPa; reef+boat=144.4±0.1 dB re 1 μPa). Spectral levels in the playbacks generally replicated the qualitative characteristics of the original recordings (Fig. 129.1b).

Over eight nights of sampling 1,932 fish (61%) were collected from reefs near a speaker playing back reef noise while only 1,229 fish (39%) were collected from reefs that had boat noise in addition to reef noise. Of the 12 species where ≥5 fish were collected, representing five common reef fish families, ten were in greater abundance on reefs without boat noise (Fig. 129.2), although due to limited replication, this difference was only significant for two species, *Pomacentrus nagasakiensis* (Nagasaki damsel; Wilcoxon signed-rank test: $n=8$, $W=36$, $P=0.01$) and *P. amboinensis* (Ambon damsel; $n=8$, $W=32$, $P=0.05$).

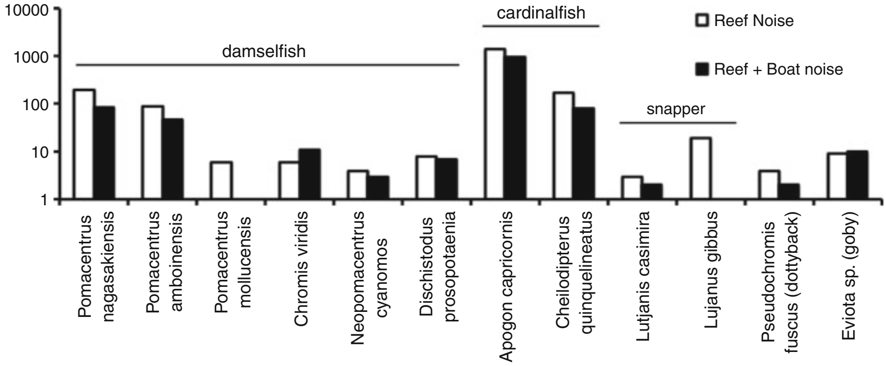

Fig. 129.2 Arrival of settlement-stage larvae and juvenile reef fish on experimental patch reefs with nocturnal reef noise or reef+boat noise playback over eight nights. Species shown are for catches of ≥5 fish

4 Discussion

When a combination of boat and reef noise was broadcast near our experimental patch reefs, we found evidence of reduced settlement of young reef fish compared with patch reefs where only reef noise was broadcast. This result suggests that boat noise may disrupt the normal process of site selection and settlement of young fish returning to reefs. Although limited by sample size, our results suggest that further investigation into the impact of boat noise on such key ecological processes occurring on coral reefs is now warranted.

Boat noise joins a growing (and worrying) list of anthropogenic impacts now thought to have the potential to influence critical life history phenomena of coral reef fishes. Conditions of ocean acidification predicted to occur later this century may also fundamentally alter patterns of replenishment (Munday et al. 2010) through effects on predator–prey relationships (Ferrari et al. 2011) and compromised behavior (e.g., Simpson et al. 2011a). A combination of noise and these other anthropogenic factors may result in the dynamics of reef fish populations becoming increasingly decoupled from the settlement processes due to maladapted orientation, habitat selection, and predator–prey interactions.

Effects of noise pollution in the world's oceans are not likely to be limited to fishes because many other taxa respond directionally to reef noise in an ecologically relevant manner. For example, anthropogenic noise has the potential to also interfere with the avoidance behavior of crustaceans (Simpson et al. 2011b) and orientation in settling crab and lobster larvae (Stanley et al. 2010, 2011, 2012) and coral planulae (Vermeij et al. 2010). Such effects may also carry through to other life history stages (see Chapter 111 by Radford et al.), given that previous acoustic experience has been shown to influence subsequent orientation (Simpson et al. 2010) and antipredator, feeding, and social behaviors (see Chapter 149 by Voellmy et al.). Because many reef fish are reared in nests on reefs by their parents throughout their embryonic stage, during which time they can detect local acoustic conditions (Simpson et al. 2005b), the potential impacts of stress from anthropogenic noise during early development (reviewed by Kight and Swaddle 2011) may have downstream consequences for the ecology of reef fishes.

Although playback of reef and boat noise does not fully replicate the acoustic conditions of natural reefs and real boats, a recent study that measured both acoustic pressure and particle velocity of ambient and boat noise and playback of recordings of these noises suggests that the signal-to-noise ratios of boat playback to ambient noise do not exceed those of a real boat (see Chapter 55 by Holles et al.). Our study represents an initial attempt to take experiments focusing on key ecological processes from the laboratory or enclosures in shallow water using captive animals to the natural setting working with wild animals. By combining these various approaches, we will develop a more complete understanding of the impact of anthropogenic noise on coral reef organisms, with the potential through management to mitigate impacts in sensitive or protected areas.

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Chapter 130
Auditory Evoked Potential Audiograms Compared with Behavioral Audiograms in Aquatic Animals

Joseph A. Sisneros, Arthur N. Popper, Anthony D. Hawkins, and Richard R. Fay

Abstract Auditory evoked potentials (AEPs) have become popular for estimating hearing thresholds and audiograms. What is the utility of these measurements? How do AEP audiograms compare with behavioral audiograms? In general, AEP measurements for fishes and marine mammals often underestimate behavioral thresholds, but comparisons are especially complicated when the AEP and behavioral measures are obtained under different acoustic conditions. There is no single representative relationship between AEP and behavioral audiograms and these audiograms should not be considered equivalent. We suggest that the most valuable comparisons are those made by the same researcher using similar acoustic conditions for both measurements.

Keywords Auditory evoked potential • Hearing • Auditory sensitivity

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1 Introduction

During the last century, behavioral studies of hearing in fishes and marine mammals peaked during an era of "ethological studies" in the 1960s and 1970s (e.g., Nachtigall et al. 2000; Ladich and Fay 2013). At that time, many investigators used behavioral conditioning techniques (e.g., classical, operant, or instrumental avoidance conditioning) combined with psychophysical methods to investigate the hearing and auditory capacities of animals (reviewed in Fay 1988). The use of behavioral techniques coupled with psychophysical methods was thought to be the ideal way to investigate hearing (Ladich and Fay 2013). However, by the late 1970s, the use of behavioral assays to test hearing in animals declined in popularity and the use of more rapid electrophysiological techniques for measuring temporary threshold shifts and for accessing auditory development in longitudinal studies became the methods of choice. In the early 1970s, a promising noninvasive technique known as the auditory evoked potential (AEP) or auditory brain stem response (ABR) recording technique was developed for use in mammalian audition studies. This technique recorded synchronous neural activity of eighth nerve fibers and brain stem auditory activity evoked by acoustic stimuli (Jewett 1970; Jewett and Williston 1971) and later became widely used and proved to be invaluable in clinical evaluations of human hearing (Hall 1992).

After its development and use in mammalian studies, the AEP recording technique became a widely used alternative method to behavioral audiogram measurements in both fishes and marine mammals due, in part, to the minimal training requirements and the reduced time to construct audiograms. The use of noninvasive techniques to investigate AEPs in marine mammals via extracranial, cutaneous electrodes was first described by Ridgway et al. (1981) and later in fishes by Corwin et al. (1982). In more recent times, these noninvasive technical methods have been further developed to investigate ABRs and measure hearing thresholds in both fishes (e.g., Kenyon et al. 1998) and marine mammals (e.g., Popov and Supin 1990; Dolphin et al. 1995). These methods haven proven to be especially useful for estimating the hearing sensitivity of animals untrained for psychophysical procedures and have been used to construct AEP audiograms for ~111 fish species (from 51 families; Ladich and Fay 2013), 15 species of odontocete cetaceans (dolphins and porpoises; see Schlundt et al. 2007; Mooney et al. 2009), 3 species of otariid pinnipeds (sea lions and fur seals; Wolski et al. 2003; Mulsow and Reichmuth 2010; Mulsow et al. 2012), and 2 species of manatees (Klishin et al. 1990; Mann et al. 2005). For some species, there exist both AEP and behavioral threshold measurements to compare AEP and behavioral audiograms, and it is important to understand how these relate, as discussed in Section 2.

Considering the broad use of AEPs and their replacement of behavioral thresholds, it is important as to whether behavioral thresholds for hearing can be estimated from AEP measurements in fishes and marine mammals. Thus, the aim of this minireview is to address some of the major pitfalls and issues of previous AEP studies and ask about when and how it is most successfully used.

2 Comparisons of AEP and Behavioral Thresholds in Fish and Marine Mammals

Comparisons of AEP and behavioral thresholds in individual fish species are limited. Recently, Ladich and Fay (2013) performed an extensive review of the AEP audiograms from over 100 fish species. Only seven of these (goldfish, *Carassius auratus*; little skate, *Raja erinacea*; common carp, *Cyprinus carpio*; European perch, *Perca fluviatilus*; red sea bream, *Pagrus major*; and Oscar, *Astronotus ocellatus*) have been investigated using behavioral as well as AEP measurements.

Among the different fish species used in hearing research, the goldfish has, by far, become the most widely used. Behavioral auditory thresholds for goldfish are quite diverse and reveal a large variation in thresholds and bandwidth (see Fig. 4 in Popper and Fay 1973). Behavioral thresholds from different goldfish studies differ by as much as 60 dB (1,000-fold) at some frequencies (Ladich and Fay 2013). These differences in thresholds and bandwidth may, in part, be due to the different behavioral conditioning methods used in these studies. However, there is a strong likelihood that the major cause of the variation is the wide range of acoustic approaches used, coupled with lack of understanding by investigators of the signal being presented to the fish (Parvulescu 1964, 1967; see Chapter 115 by Rogers et al.). In sum, the goldfish experiments are cautionary examples of how the use of different experimental acoustic conditions and behavioral conditioning techniques can affect behavioral threshold measurements.

In general, many of goldfish audiograms obtained by the AEP method are comparable in sensitivity and bandwidth with some of the behavioral audiograms, and they are somewhat less variable (20 dB variation at some frequencies). The best frequency (BF) of hearing based on AEP audiograms for goldfish is between 300 and 800 Hz, with thresholds at the BF varying between 63 and 84 dB re 1 μPa. The reported variation in AEP thresholds is likely to be the result of the different test conditions in which the data were obtained. Such test conditions may vary widely in different experimental tanks and may include the location of the speaker (in air, in water, in front or below test subject), different water temperatures (Wysocki et al. 2009), different fish sizes, and different threshold criteria. The median thresholds for all the AEP and behavioral datasets have been calculated by Ladich and Fay (2013), and they show that the median AEP thresholds are ~10 dB above the behavioral thresholds at frequencies below 1,000 Hz, but AEP thresholds are generally lower than the behavioral thresholds above 1,000 Hz. However, direct comparison of the behavioral and AEP audiograms for the goldfish is problematic and illustrates the difficulties of comparing AEP and behavioral studies for fishes in general. Audiograms can vary greatly depending on the acoustic conditions under which they were derived. Thresholds can vary by more than 30 dB just by changing the acoustic conditions (see Chapter 115 by Rogers et al.).

Therefore, it is extremely difficult to compare behavioral thresholds obtained under one acoustic condition with AEP thresholds obtained under a different acoustic condition. Making interlaboratory comparisons is virtually impossible for fish

AEP and behavioral data. This effect is “amplified” because AEPs are almost invariably recorded from fishes in very small, shallow tanks using air loudspeakers, whereas behavioral studies usually require larger tanks and immersed loudspeakers. It is evident that AEP thresholds cannot be compared with behavioral thresholds unless the fishes have been examined under very similar acoustic conditions (as in the same laboratory). However, even if the acoustic field and all conditions were controlled in the same laboratory with the same investigator, it is unlikely that the differences would disappear.

We should note here that there is also some confusion and misunderstanding in the fish AEP literature about the source of the recorded synchronous neural activity evoked by acoustic stimuli in fishes. In the mammal AEP literature, ABRs are defined as short-latency AEPs (<10 ms) that originate in the auditory periphery (hair cells and auditory nerve, AEP waves I and II, respectively), brain stem (AEP wave III), and midbrain (lateral lemniscus and inferior colliculus, AEP waves IV and V, respectively; Burkard et al. 2007). In the fish AEP literature, it is evident that what is most often recorded is the microphonic potentials from the hair cells, which produce a characteristic double-frequency response due to the presence of nonlinear and opposite-oriented hair cell populations in the auditory end organs. The activation of these opposing populations of hair cells along with any coupled afferent activation produces two evoked potentials during every stimulus cycle, thus giving a characteristic double-frequency response (Fay 1974). As a consequence, what appears to be recorded in most fish AEP studies is the evoked activity of the hair cells and perhaps their afferents rather than brain stem activity. However, most authors do not look to determine the source of their signals nor do many authors understand and appreciate this differentiation. As a consequence, some of the differences seen in “AEP” recordings from different laboratories or different species may be due to differences in the source of the actual signal and the placement of the recording electrodes.

One critical variable that warrants further discussion as a source for variation in the AEP audiogram is the actual AEP threshold criterion. In the majority of AEP studies, thresholds are subjectively determined almost entirely by the experimenters’ visual inability to separate the lowest AEP signals from electrical and other background noise (see Table I in Xiao and Braun 2008). The threshold may be determined by the observer and not the hearing thresholds of the subject. We note that the “AEP threshold” is essentially the smallest response to an electrical stimulation by auditory nerve cells that can be observed by the experimenter against electrical background noise. Some of that background noise is derived from the fish itself and may be myogenic in origin, but much of it is derived from extraneous sources.

Typically, the subjective response determination of the AEP threshold relies on visual inspection of replicate AEP averages using a subjective yes/no decision. The heavy reliance on visual inspection techniques to determine thresholds in most AEP studies is unfortunate because considerable interobserver disagreements in subjective threshold estimation have been shown in a number of independent studies by experienced trained observers or clinicians (Arnold 1985; Vidler and Parker 2004; Xiao and Braun 2008). Xiao and Braun (2008) investigated the effects of residual background noise and subjective threshold estimation of AEPs in goldfish and found that high variability in residual noise can lead to significant interobserver disagreement of AEP thresholds using subjective threshold estimation. They have proposed an objective method of threshold determination based on a comparison between AEP amplitude and controlled residual noise using a signal detection theory approach to set specific threshold criteria. We suggest that future AEP studies should include greater use of objective AEP threshold determination techniques to test hypotheses of auditory function in fishes.

As with fishes, comparisons of AEP and behavioral thresholds in individual marine mammal species are very limited. There are only six instances of both behavioral and AEP threshold measurements for odontocete cetaceans and three instances of both measurements for otariid pinnepeds (Szymanski et al. 1999; Nachtigall et al. 2005; Yuen et al. 2005; Houser and Finneran 2006; Mulsow and Reichmuth 2010; Mulsow et al. 2012). In general, most AEP audiograms underestimate behavioral thresholds in a frequency-dependent manner, with AEP thresholds being ~10 dB above behavioral thresholds at frequencies less than 30 kHz in cetaceans (Szymanski et al. 1999; Yuen et al. 2005) and at frequencies less than 10 kHz in pinnepeds (Wolski et al. 2003; Mulsow and Reichmuth 2010; Mulsow et al. 2012). The variation of AEP thresholds for marine mammals is much less than that for fishes and this is likely due, in part, to fewer acoustic issues related to the testing environment and a more consistent use of objective threshold determination techniques to construct AEP audiograms.

For example, Houser and Finneran (2006) used a number of bottlenose dolphins (*Tursiops truncates*) in a variety of test situations where acoustic stimuli were presented in tanks on shore and in a noisy bay with transducers placed in a free field and also embedded in a suction cup coupled to the lower jaw (jawphone) for stimulus presentation. Houser and Finneran found that the hearing threshold estimates of delphinids from AEPs showed similar degrees of accuracy and precision relative to behavioral thresholds regardless of the methodology used to deliver the stimulus.

Electrode placement in odontocetes may also be another factor that reduces variation in the AEP measurement. The active electrode is often placed ~6–8 cm behind the blowhole (Taylor et al. 2007), where Popov and Supin (1990) have shown that the ABR has its highest amplitude, whereas the reference electrode is placed on or near the dorsal or pectoral fin. Such consistent placement of the recording and reference electrodes may account for some of the reduced variability of AEP measurements in marine mammals. In addition, many marine mammal researchers have adopted the use of objective threshold determination techniques such as the auditory steady-state response (ASSR; Mulsow and Reichmuth 2010; Mulsow et al. 2011), a measurement similar to an AEP but obtained by objective statistical detection or by plotting the AEP response intensity (fast Fourier transform peak) against the sound pressure level of the stimulus and then using a linear regression to calculate the zero crossing point (threshold) for a given stimulus frequency (Nachtigall et al. 2007).

3 Summary and Conclusions about the Relationship between AEP and Behavioral Measurements of Hearing

Hearing is generally defined as the act of perceiving sound, a sensory function that involves the entire organism's behavior. We follow Ladich and Fay (2013) in believing that behavioral studies of hearing have a validity that AEP measurements lack.

So, where are fish AEP measurements useful? First, they are useful in getting a general sense of the range of hearing of a fish, assuming that the investigators know a good deal about (and can control) the acoustic field. Unless adequate information is presented on the acoustic field, we have no sense whether the AEP is a product of sound pressure or particle motion.

Second, AEPs can give a rough comparative sense of hearing if animals are tested in the same acoustic setup. With fishes, the different animals must generally be the same size and have swim bladders of the same volume (the swim bladder, as pointed out in Chapter 115 by Rogers et al. can alter the sound field).

Third, and most important, AEP measurements are very useful for comparing the hearing of different fish of the same species where there has been some kind of "intervention" to test some aspect of hearing. For example, studies of the effects of anthropogenic noise on fishes often explore temporary hearing changes as a result of exposure (e.g., Popper et al. 2005, 2007). AEP is a reliable measure to explore before and after hearing, and the differences found are meaningful, at least with regard to the ear and brain stem responses.

Both behavioral and AEP measurements of hearing exist for only 7 species of fish and 6 species of marine mammals, even though about 60 fish species and 12 marine mammal species have been studied using behavioral measures. In general, behavioral and AEP audiograms show a high variability among studies for both fishes and marine mammals, arising from differences in experimental conditions, and thus each audiogram, whether behavioral or AEP, must be judged on its own merits. In general, AEP measurements for both fishes and marine mammals underestimate behavioral thresholds, but in some species, these differences can occur in a frequency-dependent manner where AEP measurements result in higher thresholds at lower frequencies and lower thresholds at higher frequencies compared with behavioral measurements (e.g., the goldfish). There is no single representative relationship between AEP and behavioral audiograms and these audiograms should not be considered equivalent. We suggest that if they are to be compared, then the most valuable comparisons are those made by the same researcher using similar acoustic conditions for both measures.

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Chapter 131
Aiming for Progress in Understanding Underwater Noise Impact on Fish: Complementary Need for Indoor and Outdoor Studies

Hans Slabbekoorn

Abstract Anthropogenic noise can be detrimental to aquatic life through physical harm and behavioral impact. Physical harm to fish only occurs very close to typically brief but high-power sources. Behavioral impact occurs at more moderate levels and is spatially and temporally much more widespread. More studies are needed to get a better understanding of the behavioral impact on fish. Indoor and outdoor studies vary in their acoustic and behavioral validity and in the amount of experimental control. Although each approach has its limitations, scientific progress and applied insights will depend on the exploitation of their complementary potential.

Keywords Anthropogenic noise • Sound exposure • Behavioral effects • Methodology

1 Problem of Anthropogenic Noise

Human activities in, on, or close to water cause an artificial elevation of natural ambient sound levels underwater. Activities such as container shipping, pile driving, seismic surveys, sonar exercises, dredging, passenger transport, and motorized recreational activities have expanded over the past decades. The impact of these noisy activities on aquatic life underwater is largely unknown. However, animals from small invertebrates to large whales are sensitive to sound. For them, sound can serve a variety of functions that are critical for survival and reproduction. Anthropogenic noise can interfere with these functions and cause harm or harassment of aquatic animals. Consequently, legislators and regulators are in need of information about acoustic thresholds above which human activities compromise

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good environmental status of particular areas, negatively affect the conservation status of local populations, or induce individual take of protected species.

There are several challenges for so-called noise-impact assessments to get adequate acoustic thresholds that may be monitored and mapped for the protection of species or communities (Normandeau Associates, Inc. 2012; Slabbekoorn 2012). There is, for example, a variety of species in every underwater habitat and these species have very different sensory capacities in terms of spectral range and absolute thresholds that will determine, to a large extent, the variety in impact per species. Furthermore, the impact may be due to the particle motion or pressure component of sound or a combination of both. Extreme overexposure can cause physical damage such as barotraumatic ruptures or threshold shifts in hearing ability. More moderate exposure can have widespread effects through noise-induced behavioral changes or masking. We only just started to address these problems by assessing the thresholds and consequences of behavioral effects in a limited number of taxa (e.g., Slabbekoorn et al. 2010; Dunlop et al. 2013; Goldbogen et al. 2013; Wale et al. 2013).

2 Noise Impact on Fish

The potential for behavioral impact of anthropogenic noise on fish is, like in other taxa, related to their sensitivity to sound (Popper et al. 2004; Ladich 2008). All fish can hear and are typically sensitive to low-frequency sound below 3 kHz and many species are even limited to sound well below 1 kHz (Popper and Fay 2011). This means that high-frequency sounds, such as from mid- and high-frequency military sonar, are not expected to be problematic. However, low-frequency sounds that are associated with low-frequency sonar and almost all other sound-generating human activities are especially an issue for fish. All fish are sensitive to the particle motion component of sound because the excitation of auditory nerves is triggered by movement detection through the hair cells. Fish can also be sensitive to sound pressure, but pressure sensitivity depends on the presence of air-filled cavities in the body that can serve as pressure-to-motion transformers. Accordingly, absolute hearing thresholds and spectral ranges vary considerably among species and are related to the presence and size of a swim bladder and its proximity to the inner ear or the presence of special conductors from the swim bladder to the inner ear (e.g., Popper and Fay 2011; Schulz-Mirbach et al. 2012).

The physical impact through barotrauma or temporary threshold shifts in hearing is relatively well investigated in fish, although still not in many different species (e.g., Halvorsen et al. 2012; Normandeau Associates, Inc. 2012; Casper et al. 2013). Barotrauma is likely caused by the pressure component of sound, whereas threshold shifts through hair cell damage is more likely caused by the particle motion component. However, it has become clear that direct physical impact only occurs at very high exposure levels, which only occur very close to the source (pile-driving or detonation sites, seismic survey vessels) and typically for relatively brief periods.

Consequently, legislators and regulators should now be primarily concerned about fish behavior. Noise-induced changes in natural behavioral patterns and masking of biologically relevant sounds are less well investigated and more subtle than physical damage or death (Slabbekoorn et al. 2010). Nevertheless, behavioral effects can be highly detrimental (with consequences for long-term survival, growth, and reproduction) and can be expected as a delayed effect to localized extreme exposure but also in response to more moderate exposure. This means that the potential for behavioral effects is widespread in space and time and may concern many species and individuals.

3 Noise-Induced Behavioral Changes

Unlike physical impact, the onset of behavioral effects can start at the low end of exposure just above the threshold for detection, given the background conditions of natural ambient noise. This means that the details of hearing curves are likely to be useful to predict behavioral impact, although for most species, we lack insight into the critical ratio for sensing relevant sounds against a background of irrelevant sound (e.g., Hawkins and Chapman 1975; Ladich and Schulz-Mirbach 2013). Nevertheless, data and modeling on source characteristics and sound propagation can be used to estimate the number of animals that are exposed beyond the auditory threshold for a potential behavioral impact in the same way as for physical impact. There will also be an additional, higher threshold above which individual fish attribute meaning to the auditory sensation that may actually induce a behavioral change.

As with physical impact, an increase in the level and duration of exposure within the appropriate spectral range may result in an increased probability or stronger impact through higher arousal levels. However, this is not necessarily the case because a behavioral response may not necessarily relate to the intensity of exposure. Onset of the effect may be well beyond the level of detection and may concern anything from just a subtle gradual change to a full-extent discrete switch (e.g., a complete stop for a particular activity or a full flight response). A specific response pattern may depend on many factors such as species, sex, age, life stage, social context, abiotic conditions, previous exposure, personality (or coping style), and nutritional or motivational state (Fig. 131.1, left). Therefore, the correlation between sound exposure level and the behavioral response can be highly variable throughout the range from detection threshold to extreme overexposure. Many more studies are needed to better understand the critical factors and be able to predict this variable pattern for particular individuals of particular species in specified conditions.

Any change in behavior in response to exposure to anthropogenic noise, but also the lack of change, may have fitness consequences (Fig. 131.1, right). However, although detrimental effects may be expected, behavioral changes may also be neutral or beneficial by alleviating the noise impact on, for example, physical or physiological effects (Slabbekoorn 2012). We will only be able to get a better understanding of fitness consequences of moderate noise exposure by studying physiology and

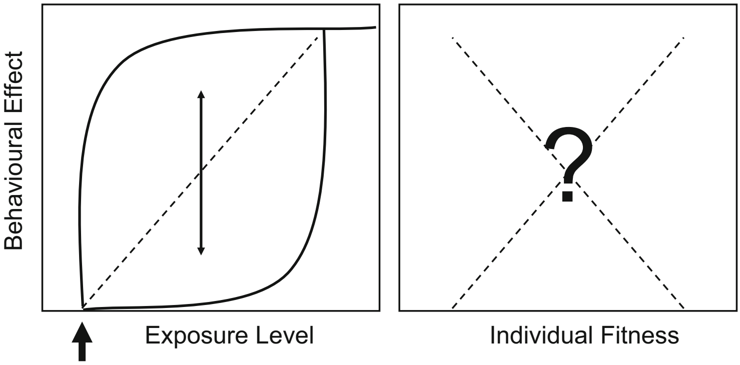
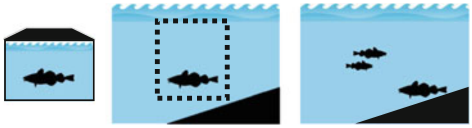


Fig. 131.1 Schematic representation about the potential impact of anthropogenic noise on behavior (*left*) and the potential consequences of noise-induced behavioral changes on individual fitness (*right*). Many factors related to sound exposure other than level, such as temporal pattern, background conditions, and those related to the potentially responding individual (see text), cause the exposure level in sound pressure (sound pressure level or sound exposure level) and particle motion to have a large range of potential dose–response patterns in terms of behavioral effect. Theoretically, anything is possible (*double arrow*), from an immediate onset of a full response close to the detection threshold (steep upward *curve* at the *bold arrow*), a gradual and linear rise in response with exposure level (*dashed line*), or a late response only at extreme exposure levels that are also close to the level of physical impact. Also, the link to fitness consequences is highly variable in potential because behavioral changes can be detrimental, neutral, or even alleviate other directly negative effects of sound exposure. We need many studies to get a better understanding of both aspects of noise impact on fish

long-term assessments on growth, reproductive output, and survival. Physiological changes that can be associated with behavioral changes (or lack thereof) can cause fitness-reducing stress, especially those that are repetitive and become chronic or go beyond levels that are within the natural regulatory range (Koolhaas et al. 2011). Furthermore, any deterrent or interruptive effect may have negative effects on feeding or reproductive opportunities or elevate costs in terms or energy expenditure or predation risk. Both the short-term physiological responses to sound exposure and long-term consequences for fitness require much more investigation, which will require both indoor and outdoor studies.

4 Acoustic and Behavioral Validity of the Indoors

Indoor and outdoor studies have both their advantages and limitations in gathering information about noise impact on natural behavior in the real world in response to human activities (Fig. 131.2). Indoor studies are often more practical and feasible to investigate the specific aspects of noise impact on fish. Also, they will usually be much cheaper and less time consuming to perform and the conditions can be more standardized than in the field. If we conduct these studies, we should be aware of the



Acoustic validity:	LOW	HIGH	HIGH
Behavioural validity:	LOW	LOW	HIGH
Experimental control:	HIGH	MEDIUM	LOW
Without limitations?	NO	NO	NO
Valuable approach?	YES	YES	YES

Fig. 131.2 Evaluation of constraints and potential for indoor and outdoor studies on the impact of anthropogenic noise on fish behaviour. Three categories of study approaches for the acoustic and behavioral validity and the potential to control experimental design, replicate adequately, and take all necessary measurements were evaluated (see text). Captive Indoor, indoor studies using fish tanks or moderately sized basins; Captive Outdoor, outdoor studies using captive fish that can move around in a restricted area; Free-Range Outdoor, outdoor studies on free-ranging fish that happen to be around the selected study area. These evaluations are crude and just a generalized assessment and should be regarded as a guide to explore potential while being aware of constraints

limitations and incorporate all relevant acoustic measurements. In this context, it is important to realize that the absolute and relative sensitivities for particle motion and sound pressure vary considerably among fish species and that we currently have hearing threshold data for very few species with measurements of both sound components (e.g., Wysocki et al. 2009; Ladich and Schulz-Mirbach 2013). Furthermore, even for the relatively well-studied species, it is typically unknown to what extent each component contributes to auditory stimulation (Radford et al. 2012). It is therefore also still unknown to what extent each component contributes to the decision making about behavioral responses and whether the variable ratio of particle motion and sound pressure could be a perceptual factor. Obviously, many more studies with adequate acoustic measurements are needed and for which one has to explicitly consider the acoustic and behavioral validity of the test conditions.

First, indoor studies in fish tanks or indoor basins can be valuable, but it should be clear that they are limited in terms of acoustic validity. Indoor sound conditions are inherently different from outdoor sound conditions (Parvulescu 1967; Rogers and Cox 1988; Akamatsu et al. 2002; see Chapter 115 by Rogers et al.). The particle motion and pressure components of sounds vary proportionally to each other in open water and in the far field away from the sound source. Using underwater speakers in a fish tank imposes problems with interpretations due to much higher particle motion levels relative to sound pressure compared with outdoor conditions. This is true throughout the tank system and most extreme close to the speaker, close to the tank walls, and close to the surface. Using in-air speakers to ensonify fish tanks provides a relatively homogeneous sound field inside the water, but in this case, particle motion levels relative to sound pressure are much lower than in outdoor conditions. These differences can explain the deviations in hearing thresholds between indoor and outdoor investigations of over 40 dB when measuring sound pressure levels and ignoring the prominent sensitivity of fish for particle motion (Hawkins and Johnstone 1978). Consequently, for any indoor experiment, we should consider whether and how the inherently artificial sound conditions affect the interpretation of results and we should be cautious in making extrapolations to the outdoor world.

Another issue with indoor studies is the limited behavioral validity of responses in captive conditions (see, e.g., Calisi and Bentley 2009). These limitations also apply to penned fish in outdoor studies that may be exposed to more natural sound conditions but that are restricted in their response by the size and location of nets. The nature and extent of behavioral responses may depend on whether fish are bred in captivity or caught and kept in captivity. Furthermore, the experience with and perception of a restricted space for swimming and escape may prevent natural response patterns, induce unnatural behaviors, and affect absolute threshold levels for behavioral responses. Consequently, for any indoor experiment, we should again consider whether the inherently artificial conditions for behavior affect the interpretation of results and we should be cautious in making extrapolations to the outdoor world.

5 Practical Challenges of the Outdoors

Outdoor studies are essential for testing the consequences and external validity of indoor findings on perceptual mechanisms and behavioral processes. Although it seems obvious that we need to go outside to study the noise impact on natural behavior in response to actual noisy human activities, there are many practical challenges to outdoor studies on unrestricted fish. First, fish are hard to see and hard to follow in their natural surroundings with typically low water transparency. Ultrasonic images may reveal short-term movements of fish for which we have a good idea about species and age class. Advanced tagging techniques may allow identification and longer term spatial monitoring. However, many factors that we would like to study and for which we need data to understand the behavioral processes often remain difficult to control or measure. It is, for example, hard to integrate these observation techniques with insight into previous exposure experience, specific social context, or perceived predation risk. Other difficult assessments in the field concern physiological measurements about nutritional or motivational state or post-exposure assessments of growth rate, reproductive success, and survival. Also, other environmental effects that can affect fish behavior may be variable and less under control, ranging from water temperature to the presence of chemical signals that may be prominent to fish but which may escape the attention of the researcher.

Experimental exposure studies are always a big step forward compared with just collecting observational data on natural occurrences because they reduce the problem of (possibly hidden) confounding factors and allow interpretations on causation. However, when targeting free-ranging fish, depending on the species, it will be hard to get adequate replicates of independent samples without unwanted biases in, for example, weather and acoustic conditions, group composition, or age class. The possibility of confounding factors or issues of sample independence should also not be neglected with indoor studies, but even relatively short-term exposure studies on the impact of variation in the temporal patterns of sound exposure still seem hard to conduct on any free-ranging fish in any reasonably replicated manner. Furthermore, the spatial and temporal variability in sound conditions can be challenging to assess at the position of the fish in terms of exposure levels, while background variability of natural ambient noise should also be taken into account. Most feasible conditions for studying causes and consequences of noise impact on behavior may be found in relatively small, territorial, and benthic species in relatively shallow water (e.g., Picciulin et al. 2010; Simpson et al. 2010; Bracciali et al. 2012; Holles et al. 2013).

Adequate replication is required with any approach and depends heavily on the specific research question. Having a clearly defined target with a matching experimental design and adequate sample size is critical for a proper evaluation of both the “internal and external validity” of significant results (Slabbekoorn and Bouton 2008). For example, comparing multiple individuals or schools in one quiet area versus multiple individuals or schools in another more noisy area may be a well-replicated case study but is still anecdotal as a general test due to the single pair of areas as replication. Also, the before, during, and after studies that are conducted with the installation of wind turbines or other large offshore construction activities typically concern unique projects with unique environmental conditions that make the data of any single project inherently unreplicated and confounded. However, the data value for progress in understanding about noise impact will come when multiple projects with comparable data are used for meta-analyses to reveal significant patterns.

6 Conclusions

Both indoor and outdoor studies have their limitations, but the way forward is to focus on their advantages and potential while being aware of the constraints (Fig. 131.2). Combining approaches and integrating indoor and outdoor studies will likely be the most fruitful way to gain insight into noise-related patterns and understanding the underlying mechanisms for behavioral changes. A large field of unknowns lies ahead of us, and it is likely that we need to gain insight step-by-step using all tools and angles available. Even anecdotal observations outside may provide useful insights into the nature of behavioral responses and already have provided many ideas about the kind of consequences that may accrue to impact on fitness. Indoor studies can be very useful to answer specific subquestions that do not rely on fully natural sound conditions and can be assessed with not fully natural response behavior. Indoor studies on hearing abilities already have contributed many insights, but integrated studies on physiology and behavior or on long-term consequences for growth, reproduction and survival are also likely to make significant progress in the controllable environment of fish tanks. The insights into behavioral processes gathered via such indoor studies will contribute to the understanding of noise-related patterns coming out of the meta-analyses based on outdoor data. Although well-replicated experimental exposure studies outdoors are likely to provide the most direct insight into pattern and process, they are also practically and financially challenging. So, for the sake of progress in fundamental science and its applied value for the conservation of fish (and aquatic animals in general), we should study the meaning of behavioral changes to anthropogenic noise exposure by exploiting the potential of all available approaches and combining techniques and conditions in a sensible and complementary fashion.

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Chapter 132
Relationship Between Hair Cell Loss and Hearing Loss in Fishes

Michael E. Smith

Abstract Exposure to intense sound or ototoxic chemicals can damage the auditory hair cells of vertebrates, resulting in hearing loss. Although the relationship between such hair cell damage and auditory function is fairly established for terrestrial vertebrates, there are limited data available to understand this relationship in fishes. Although investigators have measured either the morphological damage of the inner ear or the functional deficits in the hearing of fishes, very few have directly measured both in an attempt to find a relationship between the two. Those studies that have examined both auditory hair cell damage in the inner ear and the resulting hearing loss in fishes are reviewed here. In general, there is a significant linear relationship between the number of hair cells lost and the severity of hearing threshold shifts, although this varies between species and different hair cell-damaging stimuli. After trauma to the fish ear, auditory hair cells are able to regenerate to control level densities. With this regeneration also comes a restoration of hearing. Thus there is also a significant relationship between hair cell recovery and hearing recovery in fishes.

Keywords Temporary threshold shift • Auditory evoked potential • Regeneration • Acoustic exposure • Regression

1 Introduction

Hair cells are the mechanosensory receptors that are specialized for converting vibratory stimuli into neural signals. They are present in both the auditory and vestibular organs of the auditory system in all vertebrates (Eatock et al. 2006). Exposure to intense acoustic stimuli or ototoxic chemicals can damage these hair cells, resulting in vestibular and/or hearing loss. Although the relationship between such hair cell damage and auditory function has been well examined in mammals (Hamernik and Qui 2000; Chen and Fechter 2003; Chen et al. 2008) and birds (Marean et al. 1993; Smolders 1999), there are limited data available to understand this

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relationship in fishes. Although investigators have measured either morphological damage to the inner ear (Enger 1981; Hastings et al. 1996; McCauley et al. 2003) or functional deficits in the hearing of fishes (Amoser and Ladich 2003; Smith et al. 2004a, b), very few have directly measured both in an attempt to find a relationship between the two. Examining hair cell damage or loss through either scanning electron microscopy or epifluorescence microscopy after phalloidin labeling takes a considerable amount of time, and performing hearing tests via recording auditory evoked potentials (AEPs) takes specialized electrophysiological equipment. Because investigators may not have the time or resources to examine both hair cell loss and functional hearing loss while examining the effects of an intense acoustic stimulus or an ototoxic chemical on the fish inner ear, understanding the relationship between hair cell loss and hearing loss would help them roughly extrapolate from hair cell loss to hearing loss or vice versa. Those studies that have examined both auditory hair cell damage in the inner ear and the resulting hearing loss in fishes to understand the relationship between the two are reviewed here.

2 Previous Studies

There are currently only three published studies (Smith et al. 2006, 2011; Uribe et al. 2013) that have examined both hair cell loss and hearing loss in fishes. In each of these studies, hair cell loss was quantified by counting phalloidin-labeled hair cell bundles in specified locations along the rostrocaudal axis of the saccule. The locations were labeled as 5, 25, 50, 75, and 95% along the central axis of the saccule, with 5% and 95% being the most rostral and most caudal, respectively. Although acoustically induced hair cell loss has previously been found in the utricle (Hastings et al. 1996), these three studies focused on the saccule because it is the most well-characterized inner ear end organ in terms of fish hearing. These three studies quantified hearing loss by producing audiograms of hearing thresholds measured by AEP recording, a noninvasive method of measuring neural responses to auditory stimuli that is commonly used for measuring hearing in fishes and other vertebrates. Temporary threshold shifts (TTSs) were quantified by subtracting control thresholds from sound-exposed thresholds for each frequency tested.

The first study by Smith et al. (2006) exposed *Carrasius auratus* (goldfish) to a broadband white-noise stimulus at 170 dB re 1 μPa (or 124 dB re 1 $\mu Pa^{2}\cdot Hz$) for 48 h. Significant hair cell loss and hearing loss were evident after noise exposure, but hair cell density increased and TTS decreased over time after the exposure, suggesting that there was some correlation between hair cell density and hearing thresholds.

The second study by Smith et al. (2011) examined the tonotopic mapping of the teleost saccule by exposing goldfish to tones (0.1, 0.8, 2, and 4 kHz) at 176 dB re 1 μPa root-mean-square (rms) for 48 h. It found that the pattern of hair cell loss as a function of exposure tone frequency and saccular rostrocaudal location was similar to the pattern of hearing loss as a function of exposure tone frequency and hearing threshold frequency. In other words, in general, low-frequency exposure tones produced a greater TTS at low-frequency hearing tests and greater hair cell loss at the caudal end of the saccule, whereas high-frequency exposure tones produced a greater TTS at high-frequency hearing tests and greater hair cell loss at the rostral end of the saccule. This supported previous electrophysiological studies that suggested that there is a range of frequency sensitivities along the rostrocaudal axis of the teleost saccule.

Finally, Uribe et al. (2013) examined hair cell loss and hearing loss in response to an intraperitoneal injection of gentamicin (250 mg/kg body mass) in *Danio rerio* (zebrafish). A day after injection, zebrafish exhibited significant hearing threshold shifts and hair cell loss in both the saccule and utricle.

3 Methods

The results from Smith et al. (2011) suggested that the goldfish saccule is tonotopically organized, specifically, that regions coded as 1–3, 2–4, 3–5, and 6–7 correspond to frequency sensitivities near 4, 2, 0.8, and 0.1 kHz, respectively. In their coding scheme, the distance from the rostral tip of the saccule to location 1 is ~5%, between locations 2 and 3 is ~25%, to location 4 is 50%, and between locations 5 and 6 is 75%. Location 7 is near the caudal tip or 95% of the distance from the rostral end. To more accurately correlate hair cell loss to hearing loss, TTS data for specific hearing frequencies were paired to percent hearing loss (calculated as a percentage of control hair cell density for a given saccular location) of the saccular location that is predicted to be the most sensitive for the test frequency. For example, TTS was plotted at 4 kHz, with percent hair cell loss at 5% along the rostrocaudal axis of the saccule. Such designations for each of the three studies used in this paper are in Table 132.1. For the data from Smith et al. (2006), means of percent hair cell loss and TTS were calculated for each of the five time points after noise exposure ($N=6$/time point). Only the hair cell loss data from the 75% location were used because this caudal area had the most significant damage. Thus, only TTSs at 200 and 400 Hz were used in this analysis ($N=10$; 2 frequencies × 5 time points). For the Smith et al. (2011) data, individual fish means were averaged across all saccule locations for hair cell loss and across all frequencies tested for TTS ($N=23$)

Table 132.1 Summary of data

Study	Organism	Treatment	Saccular location vs. AEP frequency designation
Smith et al. (2006)	Goldfish	White noise (170 dB re 1 μPa rms for 48 h)	75% = 0.2 and 0.4 kHz
Smith et al. (2011)	Goldfish	Tones (0.1, 0.8, 2, and 4 kHz at 176 dB re 1 μPa rms for 48 h)	5, 25, 50, and 75% = 4, 2, 0.8, and 0.1 kHz, respectively
Uribe et al. (2013)	Zebrafish	Gentamicin (intraperitoneal injection of 250 mg/kg)	5, 25, 50, and 75% = 4, 1.5–3, 0.6–1, and 0.1–0.4 kHz, respectively

AEP auditory evoked potential, *rms* root-mean-square because of the large number of saccular locations (19) and large number of AEP frequencies tested (11) in that experiment. For the Uribe et al. (2013) data, mean TTS was plotted for each of the 10 AEP frequencies tested ($N=6$/data point).

Separate least squares regression analyses were applied to the hair cell loss and TTS versus days postsound exposure data from Smith et al. (2006) and then to the TTS versus hair cell loss data from each of the three datasets. Then, a homogeneity of slopes test was done using analysis of covariance (ANCOVA) with "TTS" as the independent variable, "study" as the factor, "hair cell loss" as a covariate, and "study × hair cell loss" as the interaction in the general linear model. SYSTAT version 13 was used for all statistical analysis (SYSTAT Software, Inc., Chicago, IL).

4 Results

There was a significant inverse relationship between hair cell loss and days postsound exposure and between TTS and days postsound exposure from the Smith et al. (2006) dataset ($P<0.001$; Fig. 132.1). Thus, as hair cells regenerated after noise exposure, functional hearing also improved. There was also a significant linear regression relationship between percent hair cell loss and TTS for each of the three studies examined ($P<0.001$; Fig. 132.2). The ANCOVA showed significant "study" and "hair cell loss" effects ($P<0.001$) but not a significant interaction effect ($P=0.67$). Thus, the linear regression relationship between percent hair cell loss and TTS significantly differed between studies, but the slopes of the three regressions were not significantly different from one another, with a 30–40% increase in hair cell loss, resulting in ~10 dB of TTS. The Uribe et al. (2013) study had a lower TTS relative to hair cell loss compared with the Smith et al. (2011) study, but the Smith et al. (2006) study exhibited much greater hair cell loss relative to hearing loss compared with the other two studies.

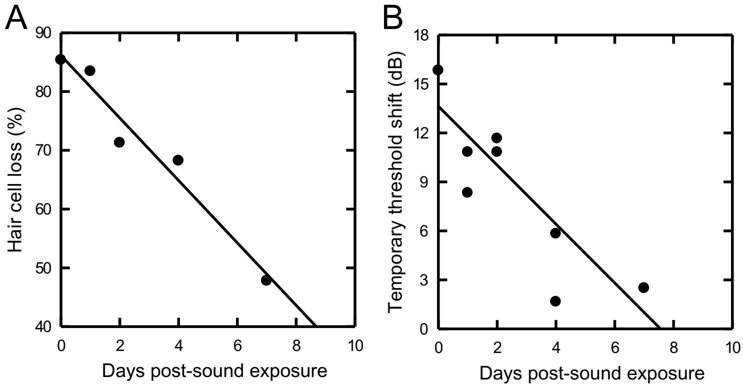

Fig. 132.1 (**a**) Percent saccular hair cell loss versus days postsound exposure (DPSE). (**b**) Temporary threshold shifts versus days postsound exposure. Significant linear regression relationships: TTS = −5.3 (DPSE) + 86.1, $R^2=0.96$, $P<0.001$ (**a**); TTS = −1.8 (DPSE) + 13.6, $R^2=0.79$, $P=0.001$ (**b**). From Smith et al. (2006)

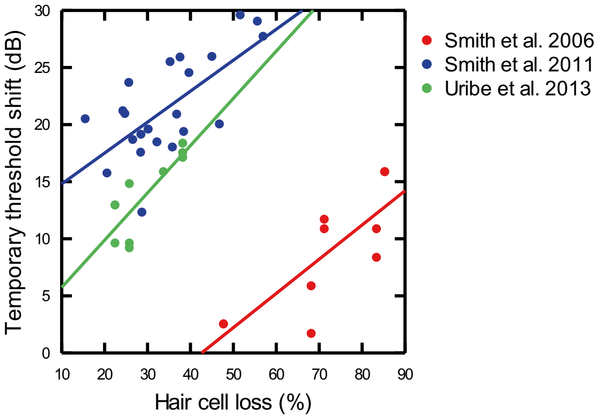

Fig. 132.2 The relationships between percent saccular hair cell loss (HCL) and temporary threshold shifts (TTSs) from three published datasets. Colored lines represent significant linear regression relationships: TTS = 2.14 (HCL) + 52.9, $R^2 = 0.64$, $P = 0.005$ (Smith et al. 2006); TTS = 1.71 (HCL) −1.9, $R^2 = 0.46$, $P < 0.001$ (Smith et al. 2011); TTS = 1.66 (HCL) + 6.6, $R^2 = 0.69$, $P = 0.003$ (Uribe et al. 2013)

5 Discussion

There is a general relationship between hair cell loss and hearing loss in goldfish and zebrafish. This is not altogether surprising because hair cells are the sensory cells that transduce auditory signals into neural ones and such a relationship has been found in other vertebrates (Marean et al. 1993; Smolders 1999; Hamernik and Qui 2000; Chen and Fechter 2003; Chen et al. 2008). The regression relationships between the Smith et al. (2011) and Uribe et al. (2013) data are similar, but the Uribe et al. (2013) data exhibited less hearing loss for a given percent of hair cell loss. This may be due to the differences in the treatment used to damage hair cells; Smith et al. (2011) used pure-tone acoustic stimuli, whereas Uribe et al. (2013) used a gentamicin injection.

The effects of aminoglycoside antibiotics on the inner ear of fishes have only been examined in four species: *Astronotus ocellatus* (oscar; Yan et al. 1991; Lombarte et al. 1993), goldfish (Ramcharitar and Brack 2010; Ramcharitar and Selckmann 2010), *Gadus morhua* (Atlantic cod; Faucher et al. 2008, 2009), and zebrafish (Uribe et al. 2013). These studies, and other studies examining hair cell loss as a result of acoustic trauma in fishes (e.g., Schuck and Smith 2009; Smith et al. 2011; Sun et al. 2011), characterize hair cell damage as a loss of hair cell bundles because this is the most clear-cut morphological measure to quantify. Of course, hearing loss could potentially result when hair cells are not completely lost but exhibit more subtle types of damage such as broken tip links between hair cell stereocilia or broken or splayed hair cell sterocilia. For example, in two reports in rats, hair cell loss was not evident until >30-dB threshold shifts had already occurred, suggesting that more subtle changes than hair cell loss was producing the hearing loss (Borg 1987; Chen et al. 2008).

In mammals, another difficulty in producing relationships between hair cell loss and hearing loss is that the cochlea has both inner and outer hair cells. Loss of the inner hair cells produces threshold shifts with no loss of tuning, whereas loss of outer hair cells produces both threshold shifts and a broadening of tuning (Liberman and Dodds 1984). Although fish sensory epithelia in the inner ear are not arranged in rows as in the mammalian cochlea, there is hair cell heterogeneity in the sensory epithelia of fish ears. For example, goldfish hair cells show ultrastructural differences such as hair cell size, afferent diameter, synaptic body size, and stereocilia and kinocilia length that vary by location on the saccule (Saidel et al. 1995; Lanford et al. 2000). How these properties or other properties such as mode of attachment to the otolithic membrane influence the propensity for hair cell damage is currently unknown. It has been noted that striola hair cell bundles are more sensitive to gentamicin damage than extrastriola bundles (Yan et al. 1991; Chang et al. 1992; Lanford et al. 2000; Ramcharitar and Selckmann 2010); thus the location of where hair cell bundle densities are quantified can make a significant difference in attempting to relate hair cell loss to hearing loss.

The reason that the Smith et al. (2006) data had less TTS and more hair cell loss compared with the other two studies is unclear. The stimulus used in that study was 170 dB re 1 µPa rms white noise for 48 h, whereas the Smith et al. (2011) study used 179 dB re 1 µPa rms for 48 h. It makes sense that the greater TTS resulted from the more intense sound stimulus, but it is unknown why white noise would produce greater hair cell loss compared with pure tones. Part of the pattern may be caused the temporal aspect of the Smith et al. (2006) data, which examined the fish at 0, 1, 2, 4, and 7 days after noise exposure, whereas the other studies examined fish soon after treatment. Smith et al. (2006) showed that almost complete hearing recovery preceded complete hair cell regeneration in goldfish, suggesting that other physiological or micromechanical properties of the sensory epithelium can compensate for missing hair cells during the recovery process. Also, the saccular location examined here was only at the 75% rostrocaudal location where hair cell damage was most evident. Hair cell loss was also significant at the 50% location but not until 2 days after sound exposure, with smaller percentages of hair cell loss and hearing loss and no significant relationship between the two (data not shown).

In conclusion, there is a correlation between hair cell loss and hearing loss in goldfish and zebrafish, but as shown here, this relationship can vary between different types of stimuli used to induce hair cell loss and will likely vary by species as well. More data are needed in which both hair cell densities and measures of hearing sensitivity are recorded, but it is unlikely that a single general predictive linear model of hair cell loss and hearing loss will be valid for all teleost species under varying hair cell-damaging conditions.

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Chapter 133
Characterization of the Sounds Produced by Temperate and Tropical Sea Urchins During Feeding (Diadematidae and Echinometridae)

Natalie Soars, Maria Byrne, and Douglas H. Cato

Abstract Despite the abundance and ecological importance of sea urchins in eastern Australia, it is not known how they may contribute to ambient noise. The sounds of feeding of two temperate and two tropical species were recorded in captivity. Most sound was produced between 2.3 and 9.2 kHz, but there were differences between species and substrate types.

Keywords Chorus • Ambient underwater sound • *Centrostephanus rodgersii*

1 Introduction

Recent studies have demonstrated the ecological significance of biological sources of reef noise to planktonic larvae. Settlement stage larvae of some tropical fishes (Tolimieri et al. 2000; Leis and Lockett 2005) as well as coral and crab larvae (Radford et al. 2008b; Vermeij et al. 2010) have been shown to use ambient reef noise to navigate toward the reef from the open ocean. Biological sound sources can provide habitat-specific information. Fish larvae can use biological sound to differentiate between reef types (Radford et al. 2011), and some are specifically attracted to the high-frequency component of reef noise produced by benthic invertebrates (Simpson et al. 2008). Information on the sources of ambient noise has the potential to be utilized for passive acoustic monitoring to detect species

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distributions and changes (Trenkel et al. 2011). Despite this, there is still much unknown about the biological sources of reef noise.

The pervasive snapping shrimp has been studied extensively as a source of biological noise in the ocean (Johnson et al. 1947; Everest et al. 1948; Au and Banks 1998), but the sound that other invertebrates may produce is not well documented. Sea urchins are widely distributed and present at high densities in reef habitats, but little is known about their contribution to ambient noise, apart from one species in New Zealand waters (Radford et al. 2008a). In this study, we characterized the sounds produced in captivity during feeding by four sea urchin species from east Australia. We investigated two temperate species (*Centrostephanus rodgersii* and *Heliocidaris tuberculata*) and two tropical species (*Echinothrix diadema* and *Echinometra mathaei*).

One tropical (*E. mathaei*) and one temperate (*H. tuberculata*) species were chosen from the echinometrid family of urchins. Echinometrids are distributed worldwide, and one species, *Evechinus chloroticus*, produces a significant chorus around 800–2,800 Hz at dawn and dusk in New Zealand (Radford et al. 2008a). One tropical (*E. diadema*) and one temperate (*C. rodgersii*) species were chosen from the diadematid family. Diadematids are known to aggregate in large numbers (Alvarado 2008), and their grazing habits influence reef community structure (Foster 1987; Tuya et al. 2004). Sound has been detected near a dense population of *Diadema setosum* (Fish 1964).

2 Methods

2.1 Aquarium Studies

Two species, *Centrostephanus rodgersii* (4 individuals, test diameter [TD] 5.5–7.5 cm) and the echinometrid *Heliocidaris tuberculata* (5 individuals, TD 7–8 cm), were collected from Little Bay, Sydney (33°59′ S, 151°15′ E). They were placed in aquariums at the Sydney Institute of Marine Science where the recordings were made. The sea urchins were placed in 45-L plastic tanks with a sandstone rock substrate free of benthic animals or plants and serviced by flow-through seawater. The aquariums were maintained with a 12:h light:dark cycle utilizing both natural and artificial light. Small sandstone rocks colonized with algae were provided as a source of food to encourage feeding behavior. Sound recordings were made over 6 days and the behavior was observed.

Echinothrix diadema and *Echinometra mathaei* were collected from the lagoon at One Tree Island and recorded in aquariums at the research station (OTIRS; 23°30′30″ S, 152°5′30″ E). Four *E. diadema* (TD 14–15 cm) and seven *E. mathaei* (TD 5.2–7.2 cm) were placed in a separate 200-L plastic tank with flow-through seawater and clean coral rubble as a substrate. The tanks were exposed to natural light. Coral pieces colonized with algae were placed in the tanks to encourage feeding behavior. Sound recordings were made over 4 days and the behavior was observed.

The urchins were recorded with a High Tech HTI-96-MIN hydrophone with a preamplifier (sensitivity −164 dB re 1 V/μPa) suspended in the water. Sound samples, 2 min in length, were recorded onto an iriver mp3 player (H10) at 10-min intervals. The system response was 20 Hz to 20 kHz. Stereo sound was recorded as a WAV file with a sample rate of 96 kHz. A 9-V battery was used to power the preamplifier of the hydrophone, while the iriver mp3 player was powered by a 12-V battery with a 5-V converter.

2.2 Analysis

Digital recordings were analyzed with a SpectraPLUS 2.32.04 using a fast Fourier transform size 4,096 with a Hanning window. For each species, spectra were produced using a mean from three feeding scrapes.

3 Results

Feeding activity on algae-covered rock or coral substrate produced rhythmic scraping or crunching sounds. These sounds were broadband, reaching the upper limit of the system frequency response of 20 kHz (Table 133.1). Generally, the greatest power was between 2,300 and 9,200 Hz, but there were differences in the peak range between species (Table 133.1). The two tropical species feeding on the coral substrate generally had more energy in frequencies >10 kHz than the two temperate species that were feeding on a sandstone substrate (Figs. 133.1 and 133.2). *Heliocidaris tuberculata* was the only species that produced significant sound at frequencies as low as 1.2 kHz (Fig. 133.1); peaks below this are from aquarium noise. Note that spectra below ~500 Hz were dominated by aquarium noise for all species.

Table 133.1 Feeding sound characteristics

	Centrostephanus rodgersii	*Heliocidaris tuberculata*	*Echinothrix diadema*	*Echinometra mathaei*
Habitat	Temperate	Temperate	Tropical	Tropical
Family	Diadematidae	Echinometridae	Diadematidae	Echinometridae
Minimum frequency, Hz	400	1,200	70	2,300
Maximum frequency, Hz	>20,000	>20,000	>20,000	>20,000
Greatest power, Hz	3,000–7,000	1,200–7,000	2,000–12,000	2,500–18,000
Peaks, Hz	1,300; 4,000; 5,500; 9,000; 12,700	1,400; 4,000; 4,700; 6,000	470; 3,000; 3,600; 8,600	2,800; 5,300; 9,800; 12,000

Values are average frequencies from 3 feeding scrapes from each of 4 sea urchin species. Estimation of maximum frequency was limited by the upper limit of the system frequency response (20 kHz)

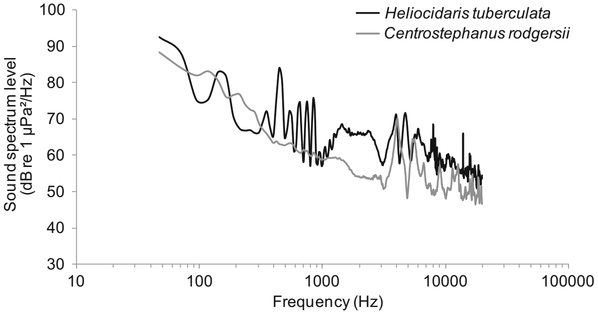

Fig. 133.1 Frequency spectrum levels of 2 temperate sea urchins, the echinometrid *Heliocidaris tuberculata* and the diadematid *Centrostephanus rodgersii.* Values are averages from 3 feeding scrapes for each species

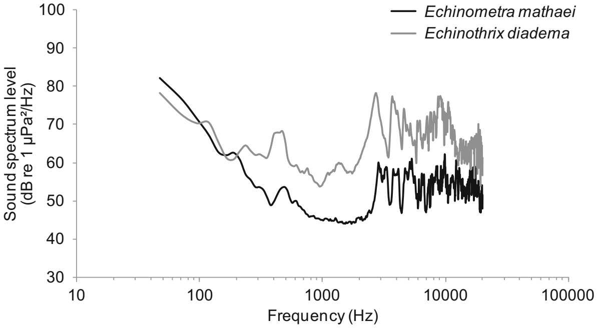

Fig. 133.2 Frequency spectrum levels of 2 tropical sea urchins, the echinometrid *Echinometra mathaei* and the diadematid *Echinothrix diadema.* Values are averages from 3 feeding scrapes for each species

4 Discussion

In general, the sounds made by the sea urchins in this study were between 2,300 and 9,200 Hz, with some variability between species. Some differences in frequencies produced between species may be due to TDs because the test acts as a Helmholtz resonator where the resonant frequency changes with size (Radford et al. 2008a). With respect to the differences in sound intensity at frequencies over 10 kHz between the tropical and temperate species, feeding on softer coral substrate may result in a greater intensity in this range than feeding on sandstone substrate. *Echinothrix diadema* was the largest species and this may be responsible for the comparatively higher sound intensity it produced.

Compared with the chorus produced by *Evechinus chloroticus* in New Zealand from 800 to 2,800 Hz (Radford et al. 2008a), the range of sounds produced by the sea urchins investigated here were usually at slightly higher frequencies.

However, *H. tuberculata*, which like *E. chloroticus* is a temperate echinometrid, did produce sound in the 800- to 2,800-Hz range.

Significantly, our study includes *Centrostephanus rodgersii*, which produces areas dominated by pink crustose coralline algae referred to as "barrens" as a result of its intensive grazing habits (Andrew and Underwood 1989). *C. rodgersii* is highly light sensitive and has a diurnal behavior pattern whereby it leaves its "home scar" at sunset, travels up to 10 m to feed, and then returns at sunrise (Jones and Andrew 1990). The range of this species has been extending southward, most likely due to the southerly transport of larvae in the warm East Australian Current (Ling et al. 2009), which is having a negative impact on commercially important abalone populations (Shepard 1973; Strain and Johnson 2009). Thus there is considerable interest in monitoring populations of this species (Byrne and Andrew 2013), potentially with passive acoustics.

It is well established that sea urchins are a significant contributor to ambient noise, particularly choruses, in New Zealand. The presence of large numbers of sea urchins along the coast of New South Wales and other locations around the world suggests that these animals could be a significant contributor to ambient underwater sound. However, the frequency of the sound they produce is likely to depend on the species and the substrate. The ecological implications of a change in frequency or an overall decrease in the ambient noise of a habitat must be considered when sea urchins are removed through fishing or other disturbances.

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Chapter 134
Acoustic Response to Playback of Pile-Driving Sounds by Snapping Shrimp

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Abstract There is concern about the effects of noise from impact pile driving as this constructional technique becomes increasingly widespread in coastal areas. The habitats of most marine invertebrate species are likely to overlap with the areas of human activities along the coast and be affected by the increased levels of noise produced. This paper investigates the acoustic response of chorusing snapping shrimp to different sound pressure levels. A significant increase in the snap number and snap amplitude was recorded during the playback of piling noise, suggesting that noise exposure affected the acoustic behavior of these animals.

Keywords Noise • Acoustic behavior • Invertebrates • Playback pile driving

1 Introduction

Many invertebrates can generate sounds to convey different information to conspecific and prey. Among crustaceans, the Californian spiny lobsters (*Panulirus interruptus*) produce pulsatile "rasps" when interacting with potential predators (Patek et al. 2009). The adult male California mantis shrimp (*Hemisquilla californiensis*) produces a "rumble" when the animal is physically handled or approached by a stick (Patek and Caldwell 2006). The most well-known biological contributors to ambient noise are snapping shrimp (*Alpheus* sp. and *Synalpheus* sp.) because their sounds are present throughout the world in shallow, warm waters (Fish 1964). The sharp snap produced individually by these animals has long been known (Johnson et al. 1947; Everest et al. 1948; Knudsen et al. 1948), and it is suggested that the shrimp use the sound to stun or even kill their prey (Schultz et al. 1998). The combined snapping within a large population of snapping shrimp may generate a continuous crackle or frying sound, creating a unique coastal chorusing (Radford et al. 2010).

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Examination of the effects of anthropogenic noise on the behavior of invertebrate species has been extremely limited and incomplete compared with the behavior of other marine animals. Over the past decades, noise from anthropogenic sources has increased in coastal habitats due to widespread constructional activities including the installation of offshore renewable energy foundations and platforms and the construction of marinas, quays, or harbors. All these activities involve driving piles of diverse sizes and materials into the seabed with a hydraulic hammer. The sounds created during impact pile driving are impulsive and reach very high sound pressure levels (Richardson et al. 1995; OSPAR 2009).

Concern has been expressed about the effects of pile-driving noise on the behavior of coastal marine animal. Several studies are available with regard to fish (reviewed in Hastings and Popper 2005; Popper and Hastings 2009a, b); however, there is a lack of scientific evidence on the possible effects of pile-driving noise on invertebrate species. A limited number of experiments have examined the effects of other sources of noise, i.e., seismic air guns (Christian et al. 2003; Andriguetto-Filho et al. 2005; Fewtrell and McCauley 2012) and boats (Chan et al. 2010), although it is difficult to extrapolate between stimuli because the sources can be significantly different in terms of levels, temporal characteristics, and frequency components (Popper and Hastings 2009b).

Behavioral changes in response to anthropogenic noise exposure are relevant because they may affect access to particular habitats including preferred feeding grounds or breeding areas. The prevalence of sounds from aquatic invertebrates suggests that sounds are important for communication and that conspecifics are capable of detecting them. Popper et al. (2001) concluded that many invertebrates are able to detect substratum vibration; however, whether these animals respond to propagated sound waves at a distance from the source remains uncertain. The present study investigated whether chorusing snapping shrimp modified their acoustic behavior during and after the playback of pile-driving noise and identified the sound pressure threshold that elicited this change.

2 Materials and Methods

2.1 Study Area

This study was carried out in Lough Hyne, a sheltered Irish marine reserve characterized by minimal anthropogenic noise and high biodiversity (Meyers et al. 1991). Background noise within the lough is dominated by high-level snapping sounds, with a single snap reaching a received level >180 dB re 1 μPa peak to peak (p-p). Three species of snapping shrimp have been known to inhabit the lough, *Athanas nitescens*, *Alpheus macrocheles*, and *Alpheus glaber* (Renouf 1931). Control exposure experiments (CEEs) were made at three different locations (Renouf Pier, Glanafeen, and Island) within the south basin where previous acoustic surveys found a high incidence of the sounds. The three locations were composed of areas of solid rock and sediment covering the rock face (McWilliam and Hawkins 2013) with a slope toward the seabed. The Island was more influenced by currents from the adjacent rapids that connected the lough to the sea. Glanafeen had more of a buildup of undisturbed sediment because it was not affected by these currents. The Renouf Pier location was at the midpoint between the Island and Glanafeen and had similar geomorphological characteristics to the Glanafeen location, but it was more influenced by the currents through the rapids.

2.2 Experimental Setup

During March 2013, a total of 96 CEEs were conducted over a period of 3 days. Twenty seconds of pile-driving noise were played back using an array of two loudspeakers connected to a Tascam DR-05 recorder and a power amplifier. The loudspeakers were placed in situ on the seabed at a depth ranging from 4 to 6 m and facing the water column above. Audio recordings were made with an omnidirectional C55 hydrophone (Cetacean Research Technology) connected to a digital recorder (Fostex FR-2LE) calibrated with a signal of 100 mV p-p at 1 kHz before the experiments took place. Recordings were sampled at 96 kHz with a 24-bit rate. The hydrophone was placed on a tripod located 0.75 m above the seabed. The distance between the speakers and the hydrophone was visually estimated at each location. The noise signal was played back at 3 different sound levels (highest level [HL] = 152 ± 0.00 dB re 1 μPa p-p; −10 dB = 145 ± 1.06 dB re 1 μPa p-p; −20 dB = 137 ± 1.71 dB re 1 μPa p-p; source levels were normalized to 7.5 m). Sound presentation included "blanks" with all the equipment in place, but the sound being played was a flat-line wave.

2.3 Acoustic Analysis

Recordings were 90 s long and included 20 s of silence before and after each playback. Sounds were analyzed with Avisoft-SASLab Pro (Avisoft Bioacoustics) sound-analysis software. For each 20-s subsample, the number of snaps was estimated by selecting a sound pressure threshold level on the raw data and counting any transient spike that was <0.2 s above the preset sound pressure threshold as a snap. This was achieved by using the pulse-train analysis function available in the sound-analysis software. A low-pass filter set at 2 kHz was applied to each sound file to filter off the playback sound. In addition, the amplitudes of each snap within each sound file were calculated. The data were pooled into different sound exposure groups based on the different sound levels (e.g., HL, −10 dB, −20 dB), and the analysis was applied during the observation of sound production under three conditions (the periods before, during, and after noise exposure). Analysis of variance (general linear model [GLM]) was used to compare differences in snap number and snap amplitude before, during, and after noise exposure at three different sound levels.

3 Results

3.1 Snap Production with Different Noise Treatments and Sound Levels

Overall, the number of snaps above background (120 ± 1.07 dB re 1 μPa) increased during playback of the piling noise (Table 134.1). Analysis of variance for the mean number of snaps counted above the background noise before, during, and after noise exposure was significant (GLM: df = 2, $F = 136.09$, $P < 0.05$). Post hoc multiple comparisons showed that the number of snaps above the background noise was significantly higher during noise exposure than before and after noise exposure at the Renouf Pier and Glanafeen locations ($P < 0.05$). The number of snaps recorded at the Island location did not show a significant increase ($P > 0.05$). Analysis of variance for snap number counted above the background noise for the different noise levels was significant (GLM: df = 2, $F = 129.82$, $P < 0.05$). Post hoc multiple comparisons showed that playback of pile-driving noise at its highest level induced a significant increase in the number of snaps recorded at the Renouf Pier and Glanafeen locations ($P < 0.05$). The increase in snap production observed during the playback at lower levels was not significant ($P > 0.05$). The Island location showed a significant increase in snap production when noise at −10 dB was played back (Fig. 134.1).

Table 134.1 Snap number and amplitude in the 3 locations recorded before, during, and after playback of pile driving at different levels

	High level		−10 dB		−20 dB	
	Snap number	Snap amplitude	Snap number	Snap amplitude	Snap number	Snap amplitude
Glanafeen						
Before	10.0 ± 6.1	182.8 ± 7.1	15.7 ± 10.7	186.2 ± 7.9	15.3 ± 13.1	185.3 ± 8.3
During	37.6 ± 26.7	193.0 ± 9.3	32.4 ± 21.1	192.3 ± 8.5	21.6 ± 15.0	188.8 ± 8.1
After	9.0 ± 5.1	182.1 ± 6.8	18.0 ± 13.7	187.1 ± 8.2	13.7 ± 10.8	184.7 ± 8.0
Island						
Before	37.5 ± 22.1	194.0 ± 8.0	38.6 ± 23.6	194.1 ± 8.1	34.6 ± 20.1	193.3 ± 7.9
During	37.4 ± 22.3	193.9 ± 8.0	39.5 ± 23.8	194.4 ± 8.0	36.5 ± 21.9	193.7 ± 8.0
After	34.6 ± 21.1	193.2 ± 8.0	40.7 ± 24.0	194.7 ± 8.0	39.3 ± 23.7	194.3 ± 8.0
Pier						
Before	58.9 ± 34.1	197.9 ± 8.1	62.9 ± 39.4	198.3 ± 8.3	64.4 ± 38.9	198.3 ± 8.2
During	98.7 ± 59.0	202.2 ± 8.4	62.9 ± 37.9	198.4 ± 8.2	62.8 ± 37.9	198.6 ± 8.2
After	61.9 ± 36.7	198.3 ± 8.2	59.8 ± 35.4	198.0 ± 8.2	61.7 ± 35.9	198.3 ± 8.1

Values are means ± 95% CI. High level = 152 ± 0.001 dB re 1 μPa peak to peak (p-p); −10 dB = 145 ± 1.06 dB re 1 μPa p-p; −20 dB = 137 ± 1.71 dB re 1 μPa p-p normalized to 7.5 m

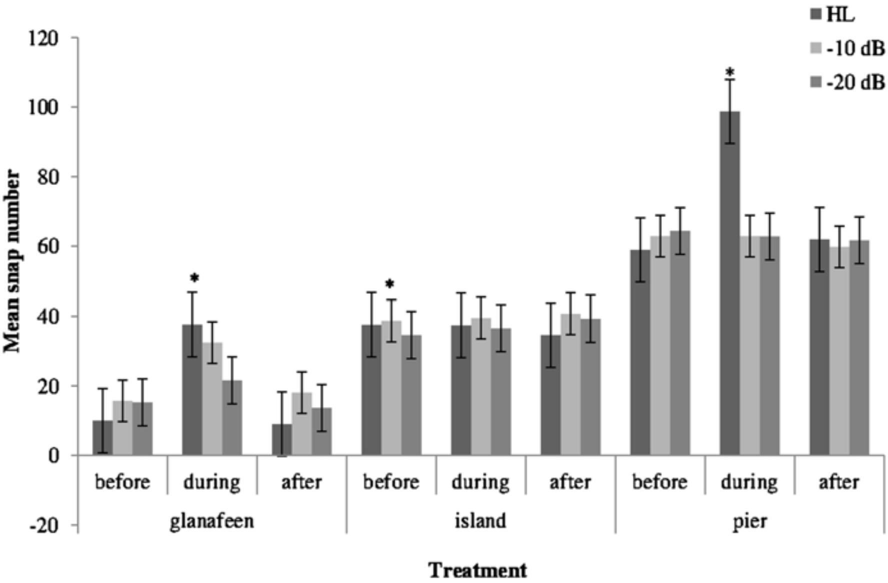

Fig. 134.1 Mean (±SE) snap numbers recorded before, during, and after exposure to noise at 3 different levels at each station. Highest level (HL) = 152 ± 0.001 dB re 1 μPa peak to peak (p-p); −10 dB = 145 ± 1.06 dB re 1 μPa p-p; −20 dB = 137 ± 1.71 dB re 1 μPa p-p normalized to 7.5 m. *, Significant difference ($\alpha = 0.05$)

3.2 Snap Amplitude with Different Noise Treatments and Sound Levels

Overall, the mean snap amplitudes increased during the playback of pile-driving noise (Table 134.1). Analysis of variance for the mean snap amplitude before, during, and after noise exposure was significant (GLM: df = 2, $F = 127.05$, $P < 0.05$). Post hoc multiple comparisons showed that the mean amplitude of snaps recorded during the playback of noise at the Renouf Pier and Glanafeen locations was significantly higher than before and after noise exposure ($P < 0.05$), whereas the snaps recorded at the Island did not differ significantly ($P > 0.05$). During playback of the noise at its HL, the mean snap amplitude recorded at the Renouf Pier and Glanafeen locations increased significantly compared with noise at the lower levels (GLM: df = 2, $F = 33.43$, $P < 0.05$). The Island location showed a significant increase in the mean snap amplitudes when a level of −10 dB was played back (Fig. 134.2).

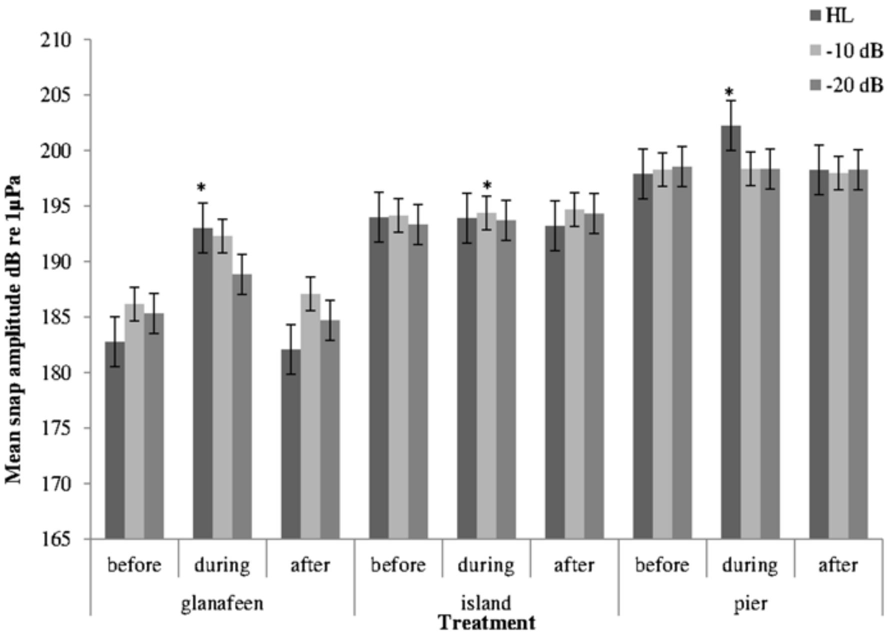

Fig. 134.2 Mean (±SE) snap amplitudes recorded before, during, and after exposure to noise at 3 different levels at each station. HL = 152 ± 0.001 dB re 1 µPa p-p; −10 dB = 145 ± 1.06 dB re 1 µPa p-p; −20 dB = 137 ± 1.71 dB re 1 µPa p-p normalized to 7.5 m. *, Significant difference ($\alpha = 0.05$)

4 Discussion

The present study has shown that chorusing snapping shrimp responded to the playback of pile-driving noise by increasing the number and the amplitude of their acoustic signals. The potential energetic cost of such a behavioral response remains unknown but it has direct implications for ocean conservation. If there are significant costs to sound production for these animals and they are being required to produce more and louder sounds to overcome the level of noise, then this could lead to detrimental impacts on the energy balance of the animals. If this balance is disrupted, this can affect species survival. Increased risk of detection by predators is another possible implication of the increase in snap production and levels observed in this study. However, considering the habitat preference of these animals, which live in burrows or sheltered locations, it seems unlikely that such a cost would play a great role for snapping shrimp.

Finally, another consideration might be of importance. The high incidence of sound production by these aquatic crustaceans suggests that the sounds may also serve other functions such as, for example, facilitating social interactions. There is evidence that snapping shrimp use the snapping sound in intraspecific agonistic interactions (Schmitz and Herberholz 1998), suggesting that these sounds are important for interindividual communication. The changes in the acoustic response of these animals to playback of the piling noise found in this study might have implications for their capacity to acoustically interact with conspecifics and communicate important biological information, affecting not only individual fitness but also population survival. In this study, it was impossible to identify whether the observed increment in the number of snaps resulted from an increased number of sounds produced by the same animal already engaged in chorusing or by the recruitment of different animals that were previously silent. If the hypothesis that these animals use sound in a social context can be further assessed, the finding of this study suggests that noise exposure might affect social interactions in a detrimental way.

Looking forward, there is a need for field-based experiments to consider the spatial scale of these demonstrated effects. Such studies should consider the particle motion component of sounds. Marine invertebrates are likely to be sensitive to the particle motion component of the sounds rather than to the sound pressure per se (Budelmann 1992a, b; Popper et al. 2001). In this study, only the sound pressure was monitored. Nevertheless, the observation that chorusing snapping shrimp in this experiment responded only to a certain level of playback pile-driving noise provides an indication of the acoustic threshold beyond which the behavior of the shrimp is affected. Further replicates of this study might help managers plan coastal developments to reduce any impact. Further studies should consider the long-term implications of the response to noise described in this paper and investigate whether similar responses occur at other locations where chorusing snapping shrimp are present.

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Chapter 135
Development of a Finite-Difference Time Domain (FDTD) Model for Propagation of Transient Sounds in Very Shallow Water

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Abstract This finite-difference time domain (FDTD) model for sound propagation in very shallow water uses pressure and velocity grids with both 3-dimensional Cartesian and 2-dimensional cylindrical implementations. Parameters, including water and sediment properties, can vary in each dimension. Steady-state and transient signals from discrete and distributed sources, such as the surface of a vibrating pile, can be used. The cylindrical implementation uses less computation but requires axial symmetry. The Cartesian implementation allows asymmetry. FDTD calculations compare well with those of a split-step parabolic equation. Applications include modeling the propagation of individual fish sounds, fish aggregation sounds, and distributed sources.

Keywords Time domain • Propagation model

1 Introduction

Underwater sounds include steady-state vessel noise, transient animal calls, and impulsive pile-driving sounds. Many propagation models use frequency-domain solutions with single frequencies. Any signal can be transformed into the frequency domain by representing it as a combination of infinite sine waves. Infinite sine waves do not represent transient and impulsive sounds efficiently because transient sounds contain many spectral components and impulsive sounds contain all

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frequencies requiring many intensive single-frequency computations. An alternate approach is to calculate sound propagation in the time domain. We developed a finite-difference time domain (FDTD) model using sample grids of sound pressure and velocity in alternating time steps to model sound propagation in very shallow water (depth ≤ 10 m). Because all calculations are done in the time domain, this approach is particularly useful for modeling the propagation of transient and impulsive sounds. In this paper, we describe the model, compare propagation calculations for single-frequency sources to the calculations of the range-dependent acoustic model (RAM) program (Collins 1995), and discuss sound-propagation calculations for various transient sounds.

1.1 FDTD Models

Yee (1966) developed the FDTD approach to model electromagnetic propagation. The approach was used by Botteldooren (1994) to model acoustic propagation in ducts and by Sakamoto et al. (2002) to model acoustic propagation in indoor spaces. The FDTD approximates the differential equations governing propagation as finite-difference equations. Spatial coordinates are computed on a grid (e.g., x_1, x_2, x_3, …), and time t is taken in discrete steps (e.g., t_1, t_2, t_3, …). Time derivatives are approximated as finite differences of time

$$\frac{\partial f(x,t)}{\partial t} \rightarrow \frac{\Delta f(x,t)}{\Delta t} = \frac{f(x,t_2) - f(x,t_1)}{t_2 - t_1} \tag{135.1}$$

and spatial derivatives are approximated as finite differences of spatial coordinates

$$\frac{\partial f(x,t)}{\partial x} \rightarrow \frac{\Delta f(x,t)}{\Delta x} = \frac{f(x_2,t) - f(x_1,t)}{x_2 - x_1} \tag{135.2}$$

The resulting finite-difference propagation equations are solved for the time evolution of the acoustic parameters pressure and particle velocity, each of which depends on the spatial variations of the other parameter.

In an approach known as leapfrogging, spatial variations of pressure are used to calculate changes to the particle velocity and spatial variations in particle velocity are used to calculate changes to the pressure. In the leapfrogging scheme, the particle velocity spatial grid points are halfway between the pressure grid points (see Fig. 135.1). The pressure and particle velocity values are computed a half time-step apart. The calculation alternates between particle velocity and pressure changes in each half time-step. We assume that the seafloor is an equivalent fluid and use its sound speed and density in the time-increment equations.

To compute propagation around barriers and in complicated indoor geometries, Sakamoto et al. (2002) used a pressure impulse as the source condition. They approximated an impulse with a pressure distribution that increases from 0 to the maximum source pressure in 10 grid spaces from each direction. For sufficiently small grid spacing, this initial pressure behaves as an impulse.

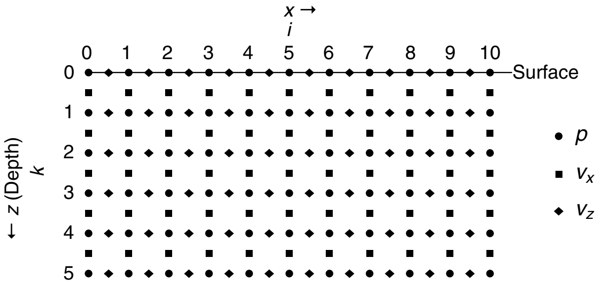

Fig. 135.1 The grid used for our finite-difference time domain (FDTD) calculations. Pressure and velocity values are separated by a half grid space to simplify finite-difference calculations involving each variable. Shown is the *x*-*z* plane, which has the same configuration as the *y*-*z* plane. In the cylindrical FDTD formulation, the *r*-*z* grid also has the same configuration. *p*, Acoustic pressure; *v*, particle velocity

1.2 Perfectly Matched Layer

One problem with finite-difference calculations is the termination of the grid space. A wave reaching the end of the grid will be reflected when, in reality, waves continue to propagate into the distance. To prevent this numerical artifact, a perfectly matched layer (PML) suppresses waves reflected from the end of the grid space (Teixeira and Chew 1997). The PML is an artificial boundary with an attenuation that increases exponentially as the grid approaches a perfectly reflecting termination. The gradual onset of the attenuation does not result in reflections as the wave enters the PML. By the time the wave propagates through the PML, reflects off the termination, and propagates back to the grid space, it attenuates sufficiently so that it does not contribute to the total sound.

2 Theory

Our FDTD model begins with the linearized acoustic equations

$$\frac{1}{c^2}\frac{\partial p}{\partial t}+\rho_0\nabla\vec{v}.=0 \qquad (135.3)$$

and

$$\rho_0\frac{\partial\vec{v}}{\partial t}+\nabla p=0 \qquad (135.4)$$

where c is the speed of sound, p is the acoustic pressure, ρ_0 is the ambient density, and $\vec{v}$ is the particle velocity. We assume that there are no significant effects of ambient flow (currents). Equation 135.3 is the linearized equation of continuity and Eq. 135.4 is the linearized momentum equation.

2.1 Cartesian Coordinates

Our three-dimensional FDTD implementation uses Cartesian coordinates x, y, and z, with z increasing in the downward direction. The grid has uniform spacing h. We assume that the seafloor is an equivalent fluid and use its sound speed and density in the time-increment equations. The water has a pressure-release surface and the grid terminates with PMLs in the other directions.

2.2 Cylindrical Coordinates

To reduce computation overhead, we assume axial symmetry and use cylindrical coordinates for range r and depth z. The 2-dimensional grid has uniform spacing h. We assume a pressure-release surface and terminate the grids on below and at high r values with PMLs.

2.3 Impulse Propagation and Source Function

We use the FDTD impulse-propagation method (Sakamoto et al. 2002) to propagate a pressure impulse from the source position(s) throughout the grid to the receiver positions. This propagated impulse response signal contains geometrical, reflective, and diffractive effects on the signal for all frequencies below the Nyquist frequency associated with the time-step Δt. The propagated-impulse response signal contains geometrical, reflective, and diffractive effects on the source signal. We then convolve the impulse response signal at the desired receiver position with the source signal function to obtain the propagated signal at the receiver position. This technique works for both steady-state and transient signals. For steady-state signals, the source function must have a duration long enough so that the transient effects vanish before the signal ends at the receiver positions. Once the transient effects at the receiver position vanish, the signal at the receiver position has reached its steady state and can be used for the propagated steady-state signal. For transient source signals, the entire propagated signal is used at each receiver position. Multiple or distributed sources are represented with pressure impulses at each source point. The impulse response signals are convolved with the source functions to obtain propagated signals. Then propagated signals from each source point are combined with any necessary time differences added.

3 Comparison with RAM Calculations

To test our FDTD propagation calculations, we computed the propagation of steady-state constant-frequency signals for various frequencies and water depths and source/receiver geometries and compared them with calculations made using a split-step parabolic equation (Collins 1993; 1994; Collins et al. 1996) calculation with the freely available RAM program (Collins 1995). We compared source signals with frequencies of 250, 500, and 1,000 Hz for several source and receiver positions and very shallow water depths and for very shallow sources and receivers in a semi-infinite ocean. Our FDTD model has good agreement with the RAM model for these frequencies and geometries. Figure 135.2 shows an example of our FDTD calculations compared with the RAM model for a water depth of 5 m and frequency of 500 Hz.

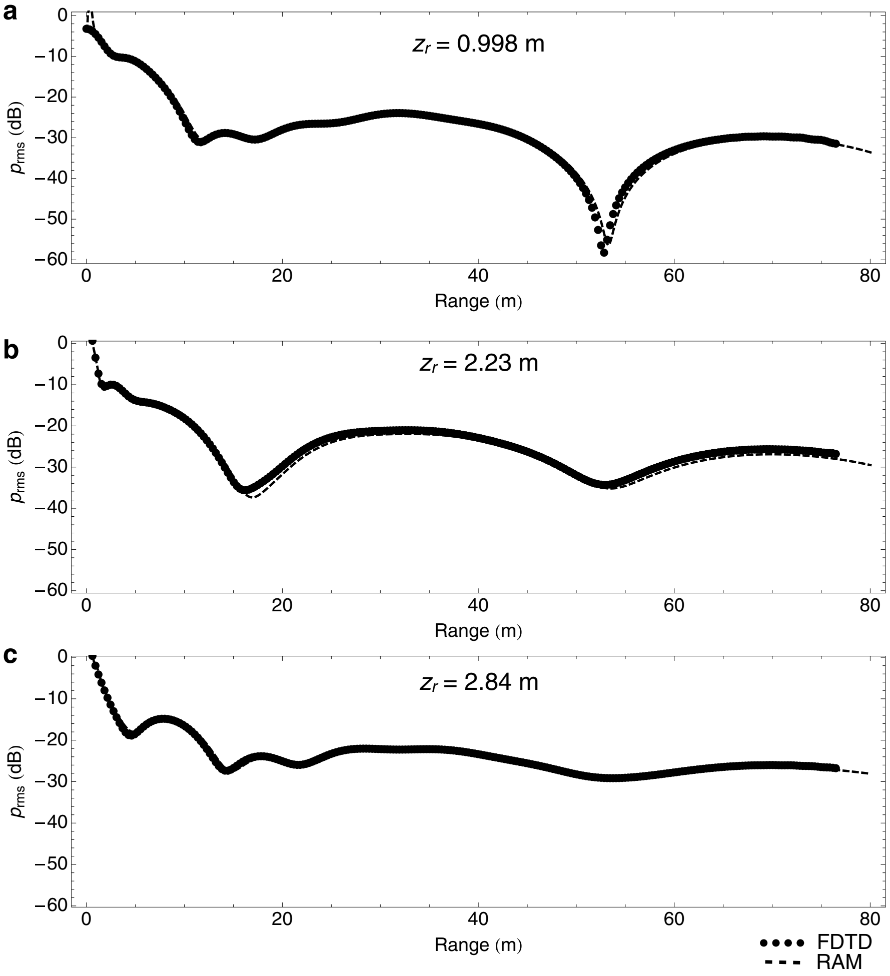

Fig. 135.2 A comparison of sound-propagation calculations produced using the FDTD model to those produced using the split-step parabolic equation range-dependent acoustic model (RAM; Collins 1995). All calculations are for a 500-Hz constant-frequency source at a depth of 2.38 m in a flat 5.00-m-deep ocean. (**a**) Receiver at depth z_r = 0.998 m. (**b**) Receiver at depth z_r = 2.23 m. (**c**) Receiver at depth z_r = 2.84 m. *rms* Root-mean-square

4 Applications

We produced our FDTD model to predict the propagation of transient sounds in very shallow estuaries and rivers (depth ≤ 10 m) where we study fish sounds and the effects of anthropogenic noise on underwater animals. Sprague and Luczkovich (2012b) used an earlier version of this model to calculate the propagation of transient *Cynoscion regalis* (weakfish) sounds in very shallow water with both level and sloped seafloors. Sprague and Luczkovich (2012a) also used the FDTD model to calculate the propagation of weakfish sounds to estimate the number of calling fish in aggregations. Another application of our model is to use the motion of a vibrating pile as the source function to calculate the propagation of the pressure and particle velocity produced during pile driving.

5 Discussion and Conclusions

We have developed an FDTD model for propagation calculations in very shallow water. We use an impulse propagation technique that can be adapted to a wide range of source functions and geometries. Our model produces propagation calculations for both steady-state and transient source functions, and it produces good agreement with the calculations produced using the RAM program (Collins 1995).

There are some downsides to the FDTD approach, though. The calculations are computationally intensive, requiring long calculation times and large storage spaces for even small 2-dimensional (cylindrical) geometries. Larger asymmetrical geometries that require the 3-dimensional implementation increase the calculation time and storage space requirements geometrically. Some of these limitations can be overcome using parallel computing platforms to produce simultaneous calculations of different parts of the geometry and large dedicated data storage systems.

Time-domain propagation models like the FDTD are particularly useful for transient signals that are compact in time but not in frequency. These transient signals include sounds of underwater animals such as fish that produce short-duration calls. We are interested in using propagation modeling to better understand the composition of calling fish aggregations and acoustic competition between fish species and to explore the possible relationships between the acoustic properties of various bathymetries and location of fish aggregations. Transient sounds produced by pile driving and other human activities are another useful application of this model. We look forward to applying our model to study these and other applications.

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Chapter 136
Vessel Noise Promotes Hull Fouling

Jenni A. Stanley, Serena Wilkens, Justin I. McDonald, and Andrew G. Jeffs

Abstract Fouling of submerged vessel hulls due to the rapid settlement of algae and invertebrates is a longstanding and costly problem. It is widely thought that the presence of extensive vacant surfaces on vessel hulls is responsible for the rapid attachment and growth of biofouling. We investigated whether noise from vessels in port could also be involved in promoting the settlement and growth of common biofouling organisms on vessel hulls. Three important biofouling species exhibited significantly faster development and settlement and better survival when exposed to vessel noise compared with control species. The extent of these responses appeared to vary in relation to the intensity of the vessel noise and may help to explain differences in biofouling observed on vessel hulls.

Keywords Vessel noise • Hull biofouling • Larval settlement

1 Introduction

Biofouling is caused by the rapid settlement and growth of marine algae and invertebrates on the submerged hulls of vessels and has been a major and costly problem since shipping began (Evans 1981; Fig. 136.1). Biofouling increases the hydrodynamic drag of a vessel, which decreases its cruising efficiency, and also increases the operating costs due to higher fuel consumption. In addition, increased financial

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Fig. 136.1 Steel-hulled vessel with biofouling in port

costs are associated with cleaning and coating the hull with antifoulants (Alberte et al. 1992; Schultz et al. 2011). For example, the overall costs associated with managing hull fouling for the US Navy is estimated to be approximately 1 billion dollars for the entire fleet of DDG-51 class destroyers over a period of 15 years (Schultz et al. 2011). Vessel biofouling also poses a significant risk for marine biosecurity due to vessel-mediated spread of invasive species (Campbell and Hewitt 2011). A single visit to a port by a vessel with biofouling species in a reproductive state can result in translocation of the organisms to surrounding vessels, port or marina infrastructure, and the environment. For example, larvae of the blue mussel *Mytilus galloprovincialis* were found to have attached to the hull of a naval vessel within 2 h of its arrival into Pearl Harbor, Hawai'i (Apte et al. 2000). Biofouling is not only a concern with large vessels but also with domestic fishing vessels and recreational vessels, which can spend significant periods of time in port, and can also be important vectors for the spread of organisms between ports (Stafford et al. 2007).

The underlying basis for the rapid settlement and growth of fouling organisms on vessel hulls is widely believed to be the availability of an unoccupied hard substrate, which is generally a scarce resource in the shallow marine environment (Wahl 1989). The movement of vessels is also thought to promote the growth of some hull-fouling organisms through improved opportunities for feeding (Lehaitre and Compere 2007). A considerable focus of attention in attempting to reduce the attachment and survival of biofouling organisms has been through the use of toxic antifouling surface coatings for hulls (Yebra et al. 2004; Schultz et al. 2011). However, the widespread use of toxic antifouling chemicals, such as copper and tin compounds, has led to restrictions on their use due to collateral environmental impacts (Champ 2000). Although a number of underwater ultrasonic devices are commercially available to help reduce hull fouling in some small vessels and oceanographic sensors (Lehaitre and Compere 2007; Gedge et al. 2012; Choi et al. 2013), their efficiency to actually reduce biofouling has not been scientifically tested. Additionally, the potential role of acoustic cues in promoting hull biofouling has been overlooked.

Among the multitude of anthropogenic noises in the marine environment, large vessels, such as those used for international trade, are the major source of underwater noise, particularly for low frequencies between 5 and 10,000 Hz (Götz et al. 2009). The low-frequency noise emitted from vessels is generated by propulsion machinery, gears, and large auxiliary engines as well as from the collapse of cavitation bubbles formed around moving propellers, power transmission units, and generators, which is transmitted into the surrounding water via the vessel structure and hull (Ross 1976). A large number of studies have described the noise emitted by vessels while underway and the effects of this noise on marine mammals and fishes (Au and Green 2000; Engås and Løkkeborg 2002; Popper 2003; Aguilar Soto et al. 2006; Codarin et al. 2009; De Robertis et al. 2010; Wood 2011; Holles et al. 2013); however, noises emitted by vessels in port and the effects of anthropogenic underwater noise on invertebrates have been largely ignored. Many large vessels that arrive in a port or marina often operate heavy machinery on deck, such as cranes and winches, as well as running noisy onboard generators to provide electricity and to power hydraulic equipment. The highest proportion of noise intensity produced by vessels in port is within the range frequency (20–2,000 Hz), a range that has also been shown to be biologically important for the attraction, settlement, and metamorphosis of a variety of marine invertebrate larvae (Montgomery et al. 2006; Götz et al. 2009; Stanley et al. 2012; Wilkens et al. 2012). Therefore, the aim of this present research was to determine whether the underwater noise produced by vessels while in port could promote the settlement of biofouling organisms.

2 Vessel Noise Promotes Biofouling in Several Key Species

Mussels are important biofoulers on vessel hulls and other industrial equipment such as seawater intake pipes (Townsin 2003; Henderson 2010; Schultz et al. 2011). Therefore, we first investigated the effects that the underwater noise emitted from a vessel in port had on the larval settlement behavior of the green-lipped mussel *Perna canaliculus*, a common biofouling species in New Zealand waters (Wilkens et al. 2012). In a laboratory experiment, the time taken by larvae to attach to the substrate (settlement) differed significantly among the three treatments (ambient vessel noise, 126 dB re 1 μPa root-mean-square [rms]; low vessel noise, 100 dB re 1 μPa rms; and silent). The time to settlement (TTS) of larvae was significantly faster when they were exposed to the ambient underwater noise produced by a 125-m steel-hulled ferry vessel in port compared with a silent control vessel. Larvae in the ambient-intensity vessel-noise treatment settled significantly faster (22% less time) than those in the silent treatment (Dunn's test: $Q = 4.0$, $P < 0.05$), whereas there was no significant difference between the low and silent (control) treatments ($Q = 2.1$, $P > 0.05$). Larvae exposed to the ambient- and low-intensity vessel noise began settling within 15 h from the commencement of the experiments compared with 40 h in the silent treatment. All surviving larvae in the ambient-intensity vessel-noise treatment had settled within 72 h compared with 96 h in the low-intensity vessel-noise treatment and 120 h in the silent treatment. There was also a trend for higher survival of larvae in the ambient- and low-intensity noise treatments, with 89% surviving versus 78% in the silent treatment; however, this was not significant ($P = 0.58$; Wilkens et al. 2012).

Given the results of the vessel noise on mussel larvae, further experiments were conducted on the larvae of an important biofouling ascidian, *Ciona savignyi*. A similar laboratory experiment was used with the same recording of the underwater noise emitted from the hull of a 126-m-long steel-hulled vessel in port and replayed at ambient (126 dB re 1 μPa rms [50–10,000 Hz]), low (100 dB re 1 μPa rms), and silent treatments. Settlement of larvae of *C. savignyi* was significantly faster when exposed to the underwater vessel noise in the ambient treatment compared with that in the silent control treatment. TTS in larvae in the ambient-intensity noise treatment was significantly faster than with the silent treatment (Dunn's test: $Q = 2.48$, $P < 0.05$), with a median TTS of 8 and 12 h, respectively. However, there was no significant difference between the median TTS in the low and silent treatments ($Q = 1.81$, $P > 0.05$). Within the first 2 h, 40% of the larvae in the ambient and low treatments had attached to the substrate compared with 11% in the silent treatment. There was also a trend of higher survival of larvae in the ambient- and low-intensity noise treatments, with 80% surviving versus 60% in the silent treatment; however, this was not significant ($P > 0.05$).

Given the apparent role of the intensity of the underwater noise produced by vessel generators in influencing the settlement of both mussel and ascidian larvae, further research was undertaken to determine if differences in the intensity of noise around a vessel may influence the degree of biofouling on the hull. Hydrophone recordings were used to determine the intensity of vessel noise at 4 locations around a 25-m steel-hulled fishing vessel while in port and operating its generator: (1) starboard side, immediately adjacent to the generator; (2) port side, directly opposite generator; (3) stern; and (4) bow (Fig. 136.2). The average noise levels at the 4 locations around the vessel hull were (1) 140.8 dB re 1 μPa rms level in the 50- to 10,000-Hz range, (2) 138.9 dB, (3) 135.3 dB, and (4) 127.4 dB and were then reproduced in a replicated laboratory experiment where the settlement behavior of a common biofouling ascidian, *Ciona intestinalis*, was measured in relation to a silent control treatment.

There was no significant difference in time to metamorphosis (TTM) in the ascidian larvae among the four vessel noise treatments (Kruskal-Wallis test, $P > 0.05$). However, the TTM in the vessel-noise treatments was significantly lower than for the silent treatment (Kruskal-Wallis test, $P < 0.05$). In the vessel-noise treatments, ~80% of the larvae had settled and metamorphosed within the first 8 h of the experiment and 100% of all viable larvae by 16 h. In comparison, larvae in the silent treatment took 16 h for 80% of the larvae to settle and metamorphose and 100% of all viable larvae by 26 h. The larvae demonstrated higher survival in the presence of noise, with the two most intense noise treatments (adjacent and opposite to generator) having 100% survival, followed by the two least intense noise treatments (stern and bow) having 94.1% and 88.9% survival, respectively, and the silent treatment having only 66% survival.

Additionally, the overall level of visible biofouling was sampled at each of the four locations, using the level of fouling scale developed by Floerl et al. (2005), around the hull of four fishing vessels of the same size and design, including the

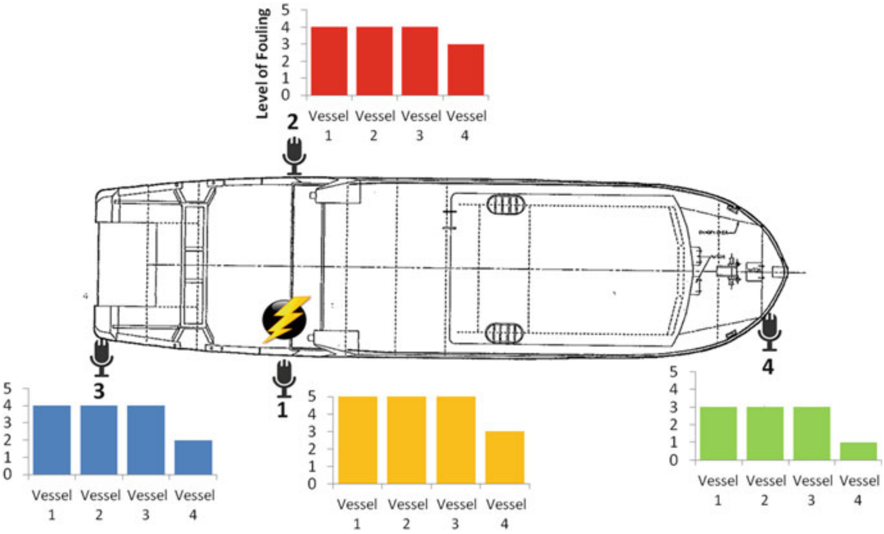

Fig. 136.2 Locations of underwater noise recordings and histograms illustrating the level of fouling on four 25-m fishing vessels. ⚡ shows location of the generator on the vessel. At each location, the hydrophone was placed 50 cm from the hull and lowered 1 m into the water column. Level of fouling: 0: 0%, none; 1: 0%, biofilm; 2: 1–5%, light biofouling; 3: 6–15%, considerable biofouling; 4: 16–40%, extensive biofouling; 5: 41–100%, very heavy biofouling (Floerl et al. 2005)

same vessel that was sampled for vessel generator noise. A significantly greater level of fouling was found to be associated with the hull location immediately adjacent to the generator (starboard side), which had a higher underwater noise level in the vessel sampled (140.8 dB) compared with the three other hull locations (opposite generator portside, stern, and bow; $P = 0.01$; Fig. 136.2). This pattern of biofouling was mostly consistent around the hulls of the four fishing vessels that were sampled. There was also a significantly higher number of species at the hull location immediately adjacent to the generator in three of the vessels ($P = 0.003$); however, in the fourth vessel, the species diversity was highest on the stern hull location, followed by the generator location (starboard side). This result may have been due to heavily fouled netting that was submerged from the stern of this particular vessel.

3 Conclusions

The results of these studies provide the first evidence that the larvae of at least two important hull fouling taxa, ascidians and bivalves, are capable of detecting and responding positively to the underwater noise associated with vessels running on generator power while in port and that these vessels may be increasing their biofouling by emitting attractive acoustic signals. The larvae of *P. canaliculus, C. intestinalis*, and *C. savignyi* all exhibited a faster TTS and TTM and improved survival with exposure to vessel noise.

Stationary vessels in port not only provide a suitable settlement surface for the larvae of hull fouling species but also emit underwater noise that promotes behavioral and physiological changes involved in settlement as well as possibly enhancing larval survival. Methods for reducing marine biofouling on vessels and preventing invasive species from establishing need to be further investigated because shipping is recognized as a major vector for the translocation of marine species (Hewitt and Campbell 2010; Campbell and Hewitt 2011), which is a major threat to marine biodiversity (Bax et al. 2003). Strategies to control the underwater noise emitted from vessel hulls may assist with reducing hull biofouling and, consequently, the risk of marine species translocations.

4 Future Studies

Because vessel noise appears to be an important factor in promoting hull fouling, methods such as dampening and reducing noise emissions from vessels in port or switching to a shore-based power supply as opposed to using vessel-based generators may help to reduce this problem.

Further investigation into the specific frequencies attractive and unattractive to the larvae of target biofouling species is also needed. Once identified, the operation of onboard machinery could be "tuned" to reduce the larval settlement of hull biofoulers. Also, further investigation of particle velocity and vibration characteristics on hull and around hull surfaces is needed.

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Chapter 137
Potential Uses of Anthropogenic Noise as a Source of Information in Animal Sensory and Communication Systems

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Abstract Although current research on the impact of anthropogenic noise has focused on the detrimental effects, there is a range of ways by which animals could benefit from increased noise levels. Here we discuss two potential uses of anthropogenic noise. First, local variations in the ambient-noise field could be used to perceive objects and navigate within an environment. Second, introduced sound cues could be used as a signal for prey detection or orientation and navigation. Although the disadvantages of noise pollution will likely outweigh any positive effects, it is important to acknowledge that such changes may benefit some species.

Keywords Ambient-noise imaging • Acoustic daylight • Prey detection • Acoustic landmark

1 Introduction

All sensory systems are affected by noise when acquiring information from the environment. Current research on the effects of noise has focused on the detrimental effects and how animals deal with interference from noise (Brumm and Slabbekoorn 2005). Recent concerns about sound pollution have led to several studies on the effects of anthropogenic noise on animals (see reviews by Nowacek et al. 2007; Barber et al. 2009; Slabbekoorn et al. 2010). At its most extreme, noise pollution can have pronounced population-level consequences such as lethal beaked whale strandings in relation to Navy sonar exercises (Tyack 2009). Other more common effects are temporary or permanent damage to the auditory system, avoidance responses leading to changes in local abundance and distribution, masking of

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communication or other sound cues used as information sources, distraction from relevant signals, increased stress levels, hypertension, and decreased reproductive success (Nowacek et al. 2007; Barber et al. 2009; Chan et al. 2010). Thus, noise is now seen as a major environmental problem that requires mitigation strategies.

Although most studies highlight the detrimental effects of noise, increased noise levels can also be beneficial to some species. There is now a much greater recognition of how animals use sounds outside of direct signal exchanges. Eavesdropping on conspecific and other species' communication signals or movement sounds are much more widely used as sources of information about predator or prey presence and habitat choice than previously assumed (Deecke et al. 2002; Barber et al. 2009).

Similarly, anthropogenic noise can be beneficial to some species depending on context and how others react to it. For example, prey of greater mouse-eared bats (*Myotis myotis*; Schaub et al. 2008) and western scrub jays (*Aphelocoma californica*; Francis et al. 2009) experience a decrease in predation pressure due to predators avoiding increased local noise. Similarly, masking of movement sounds by anthropogenic activity may decrease foraging success in predators benefiting prey species (Barber et al. 2009). Conversely, this acoustic crypsis could also allow predators to avoid detection by prey and increase their foraging success (Chan et al. 2010).

Although these examples are seen as the main possible benefits of noise in the recent literature, there is a range of mechanisms by which animals could potentially benefit from noise. Here we discuss two other potential uses of sound. First, local variations in the ambient-noise field could be used to perceive objects and navigate within an environment. Second, introduced sound cues could be used as a signal for prey detection or serve as acoustic landmarks for orientation and navigation.

2 Use of Local Variation in the Ambient-Noise Field to Detect Objects

One potential information stream provided by anthropogenic noise is from detectable differences within the ambient-noise field. Variation in the ambient-noise field can provide information on an object through the presence of an "acoustic shadow." In the visual domain, one way to detect objects is to use the differences in illumination (i.e., shadows and reflections) created between an object and a directional point source such as the sun. In the acoustic domain, there is often no dominating source of illumination, and the noise field is typically made up of a myriad of different natural and anthropogenic sources. However, in some cases, the ambient-noise field will contain localized sound sources such as snapping shrimp on fringing reefs or breaking waves around isolated rocks. In such circumstances, reflectors may cause acoustic shadows that would manifest as local attenuations in the noise field. Directional hearing and sound source segregation could allow an organism to detect the change in the ambient-noise field and detect the object.

Another way of gathering information using the acoustic ambient-noise field is with "acoustic daylight" or "'ambient-noise imaging" (ANI). Objects can be detected using incoherencies within the ambient-noise field as a main source of illumination (thus providing acoustic daylight; Buckingham et al. 1992). In this case, reflective objects will modify the ambient-noise field, creating a source of information that can be extracted through different methods. In engineering applications, imaging of reflective objects has been achieved by focusing scattered sound onto a paraboloid reflector, essentially creating an "acoustic lens" (Buckingham et al. 1992). More accurate pictorial images can be created by using a paraboloid reflector in conjunction with a hydrophone array that enables beam forming and mapping of relative intensities in each beam (Epifanio et al. 1999). Acoustic daylight imaging has led to the successful development of a computerized detection system, ADONIS, capable of using ambient noise to detect underwater objects (Epifanio et al. 1999). This system was able to detect various objects including 1-m-wide neoprene and corrugated steel targets, a swimming diver, and 113-L polyethylene drums filled with air, wet sand, and seawater at distances of at least 40 m (Epifanio et al. 1999).

In animals, the use of ambient noise for object imaging would be limited by having only two ears functioning as receivers. Although spatiotemporal integration and directional hearing could solve some of these issues, real imaging such as in engineering applications is unlikely to be possible. Nevertheless, the basic forms of ANI, such as for the detection of large obstacles, have been successfully shown in humans (Ashmead and Wall 1999). Some additional evidence suggests that human subjects were capable of determining an object's size (Gordon and Rosenblum 2004) and shape (Rosenblum and Robart 2007) in a continuous broadband noise field.

To date, no study has directly investigated whether animals use this information. However, based on theoretical models, it has been suggested that animals are capable of using acoustic daylight imaging for navigation and object detection (Potter 1997). Some empirical studies may also point toward such abilities even though alternative explanations cannot be ruled out. Blinded rats (Riley and Rosenzweig 1956) and seals in darkened environments (Oliver 1978) have been shown to perform well in navigation and obstacle avoidance experiments. It is possible that changes in the ambient-noise field were used for navigation. However, it is also possible that the seals detected hydrodynamic disturbances, using their vibrissae to navigate (as shown in Dehnhardt et al. 2001).

The ability to utilize ambient noise may also explain the presence of advanced auditory capabilities in fish species that do not produce sounds themselves (Fay 2009). For example, the goldfish (*Carassius auratus*) does not use any known form of sound communication, but it has a very acute sense of hearing (Fay 1998). Rather than being used for communication, it is possible that the fish use their sensitive hearing to exploit ambient-noise information. Although this possibility has not been well investigated, Lewis and Rogers (1992) demonstrated that fish have the potential to use ambient noise to detect other fish. They successfully conditioned fish to discriminate between artificial Gaussian noise fields, either without any scattering or with scattering similar to that which would occur from resonance in swim bladders (Lewis and Rogers 1992).

Anthropogenic noise could enhance or impede ANI. In situations where anthropogenic noise sources are highly localized, they may increase incoherencies in the noise field and therefore provide additional acoustic "illumination," resulting in improved object detection capabilities for animals. However, it is also possible that anthropogenic noise sources can reduce inhomogeneity in a noise field by interfering with natural point sources or could mask localized ambient-noise cues and prevent the perception of certain types of reflection patterns.

Currently, few studies have addressed the use of acoustic daylight imaging by animals. It is therefore difficult to predict how specific anthropogenic noise sources would affect an animal's perception. Further research investigating the abilities and detection sensitivities of animal species of interest would be valuable.

3 Use of Noise as a Signal for Prey Detection

Many species use passive listening to movement sounds to detect and capture prey (e.g., dolphins, Gannon et al. 2005; bats, Schaub et al. 2008). Through learning, animals can associate specific sound stimuli with food availability. This would be most obvious where anthropogenic noise indicates prey patches. In the marine environment, anthropogenic noise from fishing boat engines, pingers, sonar, and acoustic deterrent devices used on fish farms could be used by predators to locate prey, resulting in a "dinner bell" effect. Marine mammals have been found to be attracted by such sounds (Chilvers and Corkeron 2001; Thode et al. 2007), occasionally even to sounds introduced with the intention of deterring them (Bordino et al. 2002). In wild populations, higher incidences of predation at fisheries with acoustic deterrent devices (ADDs) may be attributed to learned associations between sound and prey (Jefferson and Curry 1996). ADDs produce loud sounds that are believed to cause avoidance responses in species such as seals that depredate fish farms. Although seals that have not previously been exposed to these avoid them, seals that have experience finding fish at that location quickly habituate to ADD sounds (Götz and Janik 2010, 2013). Through operant conditioning, ADDs can be associated with the presence of fish and then act as a dinner bell, potentially attracting seals to the area.

Current research using artificial sound sources to mark fish, such as the ocean-tracking network (http://oceantrackingnetwork.org/; Cooke et al. 2011), could also be influenced by such an effect. Many of these studies use acoustic coded transmitters (also known as pingers) that typically emit an ultrasonic acoustic signal that is inaudible to fish but is audible to many marine mammal predators (Bowles et al. 2010). If the signal is detectable, the sound would be associated with the presence of prey and could cause increased predation through a learned dinner bell effect. Alternatively, marine mammal predators may initially avoid fish fitted with a pinger, thus reducing the predation of tagged fish. In either case, such tag effects cause significant differences in the mortality of tagged compared with untagged fish and therefore lead to erroneous conclusions when studying fish behavior and survival rates.

Most of the studies illustrating the use of anthropogenic sound as a signal for prey detection are opportunistic. It is currently unclear to what extent acoustic cues affect prey detection or how long it would take for a predator to make an association between novel sound and an associated food source in its natural environment. However, the first results show that some predators like bottlenose dolphins (*Tursiops truncatus*) use fish communication sounds to detect prey aggregations (Gannon et al. 2005). Thus, more controlled studies investigating the role of anthropogenic acoustic information in prey detection are needed.

4 Use of Noise as a Signal in Orientation

Although noise can be used to navigate within an environment, it can also be used as a signal to mark specific locations. Apart from the effects of habituation and sensitization, the role of learning in reactions to noise is often overlooked. However, changes in the acoustic environment of an animal may be used to inform the receiver about the features relevant to its survival. Animals may use novel noise sources as an indicator of locations of interest and therefore are vulnerable to changes in the noise field.

This is particularly a concern with the introduction of anthropogenic noise. Sounds of ocean features such as reefs have been found to inform fish of their location (Simpson et al. 2005). For example, several species of reef fish have been shown to be attracted to the location of artificially simulated reef sounds, especially during larval stages (Leis et al. 2003; Simpson et al. 2004). Damselfish (*Pomacentrus* sp.) have been found to develop a preference for settling locations that have the same soundscape as the one that they experienced as larvae (Simpson et al. 2010). Additionally, ocean noise caused by waves or currents is suspected to be an important cue in the migration and orientation behavior of marine mammals (Richardson et al. 1995). Introduced anthropogenic noise may mask other such signals and affect navigation.

Stationary anthropogenic noise sources an also be used as a navigational signal or acoustic beacon. This can be advantageous or of concern depending on when and for how long noise is introduced into the environment. Exposure to anthropogenic noise may lead an animal to use the novel sound source as a signal, functioning as an acoustic landmark for orientation. However, when the sound is removed or relocated, this could confuse animals and create navigation errors. Currently, very little is known about the role of acoustic landmarks in animals, but there are numerous examples of the use of visual landmarks in navigation (for example, honey bees, *Apis mellifera*, Cheng et al. 1987; domestic dogs, *Canis familiaris*, Milgram et al. 1999; desert ants, *Cataglyphis fortis*, Collett 2010;). It is difficult to predict what role anthropogenic noise sources may play in animal navigation. Additionally, no information is available on the time it would take for an animal to associate locations with a novel sound source or how relocation of a sound source would affect its use as a beacon. Thus, future research investigating the role of anthropogenic sound in navigation would be valuable.

5 Conclusions

At present, very little is known about how animals utilize sound information other than that from species-specific sounds. Our ability to evaluate the effects of anthropogenic noise on a population level is hampered by a lack of understanding of how animals deal with noise. It is often assumed that noise can only compromise the fitness of animals. Although the disadvantages of noise pollution will likely outweigh any positive effects, it is important to understand how learning and perceptual mechanisms might be influenced by noise. Rare studies acknowledge that noise may have no effect or might even benefit some species.

We focused here on the use of ambient noise for acoustic daylight imaging, in which ambient noise from anthropogenic sources could help to illuminate the environment and aid sensory perception, and the use of anthropogenic sound as a signal marking locations for navigation or prey detection. The effects on species distribution and composition at locations of increased noise levels may create further advantages for selected species. To assess the role these effects might play, further work is needed on how animals use sound and react to it, especially concerning the sensitivities for perception and learned associations with sound.

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Chapter 138
Active Acoustic Monitoring of Aquatic Life

Peter J. Stein and Patrick Edson

Abstract Active acoustic monitoring (AAM) can be used to study the behavioral response of marine life and to mitigate harm during high-danger anthropogenic activities. This has been done in fish studies for many decades, and there are now case studies in which AAM has been used for marine mammal monitoring as well. This includes monitoring where the ranges, AAM frequency of operation, and species are such that the AAM operation is completely outside the hearing range of the animals. However, it also includes AAM operations within the hearing range of marine life, although this does not necessarily that imply AAM is not a suitable tool. It is just not always possible to have a sufficient detection and tracking range and operate at a frequency outside the marine life hearing range. Likely, the best and most important application of AAM is when the anthropogenic activity to be conducted is temporary and presents a clear danger to aquatic life.

Keywords Marine mammals • Fish • Sonar • Noise • Mitigation

1 Introduction

In-water monitoring and assessment of aquatic life, particularly kinematic behavior relative to anthropogenic activities and structures, is a complex problem. Indications of avoidance or attraction, in addition to the possibility of temporary or permanent damage to the animals, may occur at relatively large distances (on the order of hundreds of meters) or very close to the activities or structures. They may occur at the surface or at depth. They may also be subject to changing conditions on time scales ranging from tidal flows to diurnal cycles to seasonal changes. As such, it is unlikely that a single assessment technique will be best suited to all ranges, marine life, and environmental conditions. However, in cases where the highest likelihood of detection, localization, and tracking is required, e.g., in the vicinity of high-danger

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activities such as explosives work or pile driving, active acoustic monitoring (AAM) is generally the most robust method.

One significant disadvantage of AAM is the potential for negative side effects on marine life due to active acoustic transmission. Another consideration in trying to determine avoidance reactions involves possible ambiguity as to whether a change in behavior is due to the AAM system or the anthropogenic activity being studied. The spectrum of acoustic frequencies audible to the mix of species present in a given environment is often rather broad and may range from tens of hertz to hundreds of kilohertz. In many applications, it may not be feasible to select an active acoustic system that operates outside the hearing range of marine life near these anthropogenic activities. However, the ability to control the parameters of an AAM device, features such as frequency, source level, and duty cycle, may, in many cases, be a far safer alternative as a detection and alert technique to prevent substantial injury from activities that cannot be sufficiently mitigated (e.g., pile driving). It may also be the only feasible mechanism for monitoring marine life behavior (e.g., avoidance and attraction) around anthropogenic structures such as marine hydrokinetic turbines.

1.1 AAM

Active acoustics is where sound transmitted by an acoustic source travels out to a target, reflects off the target, and travels to and is detected by one or more receivers. At least one receiver is usually collocated with the source. Through measurements of travel time and a plethora of characteristics of the return signal, sonar systems are able to perform detection, localization, tracking, and classification (DLTC). The level of performance depends on the specifics of the system and the environment. However, in most circumstances, active acoustics or active sonar is truly the only viable solution for knowing with certainty whether and where there is an object in the water column. In one recent example, an extensive four-phase study (Hastie 2012) demonstrated the potential of using very high frequency active sonar to track marine mammals, specifically harbor seals, at short ranges near a tidal turbine (generally <50 m).

Despite variations in performance, active acoustics is often the only reliable method to detect and track marine life. Passive acoustic methods depend on vocalizations that are not guaranteed to be present when needed. Radar, thermal imaging, and visual cameras may be successful for some forms of surface interactions but are largely unusable for objects at depth. In addition to the physics described in Section 1.3, active acoustics is primarily inhibited by two features: possible effects on marine life for which the goal is to protect and systems that work are often expensive and have limited coverage.

1.2 Primary Performance Considerations

Of course, sonar is a well-developed and understood technology. Active sonar systems exist to track submarines, find fish, detect and map the bottom (depth sounders and side-scan sonar), and provide imaging of the underwater environment.

Table 138.1 One-way propagation loss as a function of frequency assuming spherical spreading and nominal absorption values

Frequency (kHz)	Absorption (dB/km)	One-way propagation loss (dB)		
		10 m	100 m	1 km
N/A	0	20	40	60
50	12	20	41	73
100	26	20	43	90
200	44	21	44	110
400	88	21	49	154

However, their capabilities depend greatly on the system configuration and the operating frequency. Operating at higher frequencies offers several distinct benefits. The ability to accurately localize and image is related to the size (aperture) as a function of wavelength (or inverse frequency), and operating at higher frequency, the transducer is small relative to its resolution. In addition, the target echo strength is generally stronger at higher frequencies. Finally, operating at higher frequencies (high tens to hundreds of kilohertz) will push the transmitted sound outside the hearing range of a larger subset of marine life (Southall et al. 2007).

The most significant impediment to increasing the frequency of the transmitted sound is the absorption of sound in seawater, which increases dramatically with frequency. Increased absorption rapidly reduces the possible detection range as seen in Table 138.1. Table 138.1 shows the one-way propagation loss as a function of frequency (and associated absorption) and range, assuming spherical spreading (absorption values for 10 °C, 30 ppt salinity; Ainslie and McColm 1998). Beyond 100 m, the expected received level drops significantly based on the one-way propagation loss. By 400 kHz, losses become significant even at 100 m, with an additional 18-dB round-trip loss compared with 50 kHz.

Sonar systems generally operate with detection thresholds on the order of tens of decibels or less. For this reason, the maximum range of a sonar system operating at a particular frequency can be approximated by determining the range at which the losses due solely to absorption (not geometric spreading) equal 10 dB. From a practical system-design standpoint, as the range increases beyond this point, the losses due to absorption begin to dominate and the signal-to-noise ratio rapidly decreases and becomes negative. Said another way, given the maximum desired detection and tracking range, the maximum operating frequency of the sonar system is given by the frequency that results in a 10-dB absorption loss at this range (or 20-dB round-trip absorption).

Figure 138.1 illustrates this approximate maximum operating frequency as a function of desired detection range using absorption values for three different temperature values (35 ppt salinity, 8.0 pH; Ainslie and McColm 1998). Figure 138.1 also includes known operating ranges for five example systems as well as also showing the hearing range for the marine mammal functional hearing groups (Southall et al. 2007). In a great many cases, it is impossible to get a significant detection and tracking range while also not being within the hearing range of the species of interest, although the exception to this might be the low-frequency cetaceans. Thus a balance must be struck between the danger of the activity of interest and the effects of the AAM system.

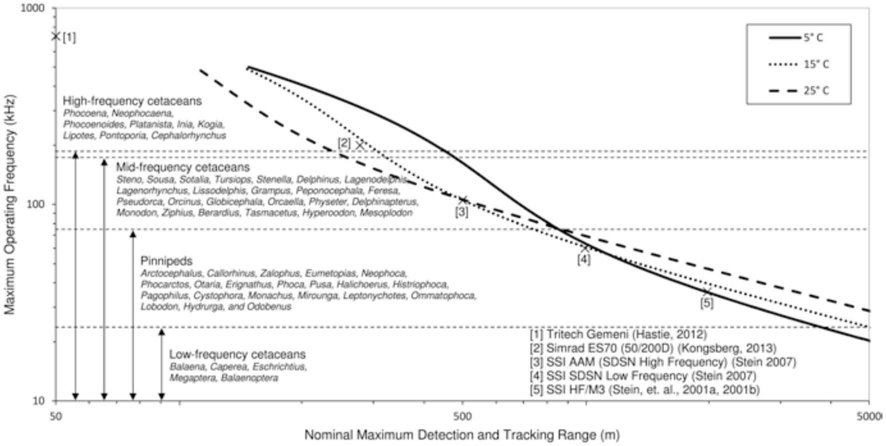

Fig. 138.1 Approximate maximum operating frequency as a function of detection range due to absorption limitations compared with known operating ranges for 5 example systems and the hearing range for the marine mammal functional hearing groups

This will be very specific to the activity and the species being protected or studied. To utilize the AAM systems, there need to be substantial studies on the effects of the AAM systems themselves on various species.

As an aside, it is important to note that once operating outside the hearing range of the marine life, active sonar is very safe. One way to consider this is the total acoustic power that could be absorbed by an animal at some distance from the sonar system. This is given by the equation

$$P_A = \varepsilon \frac{A}{4\pi R^2} 10^{\frac{(L_S - 171)}{10}}$$

where P_A is the average total acoustic power in watts that could possibly be absorbed by the animal, A is the cross-sectional area of the animal intersecting the acoustic wave, R is the range (the equation assumes spherical spreading), Ls is the source level in decibels re 1 μPa^2 at 1 m, and ε is the duty cycle (sonar transmit pulse length in time divided by the repetition rate). As an example, an large animal like a whale that presents a 5-×2-m cross section at a range of 100 m from a sonar with a source level of 220 dB re 1 μPa^2 at 1 m and a 2% duty cycle could only possibly heat the animal with –0.12 W (only a fraction of a flashlight bulb wattage). At a range of 10 m, this goes up to roughly 12 W, which is obviously also insignificant for such a large animal.

Other useful models of potential tissue damage due to acoustics above the hearing range come from the medical use of ultrasound (Nyborg 1981). In these scenarios, the concern of acoustic hyperthermia involves localized temperature rises and associated cellular damage. The simplest calculation for the temperature rise is

$$T = \frac{2\alpha I}{\rho C}$$

where I is the time-averaged intensity, α is the tissue absorption, C is the tissue specific heat, and ρ is the tissue density (Fry and Fry 1950). To achieve even modest temperature changes, on the order of a 1 °C increase, local peak pressures at 1 MHz are required to be ~1 MPa given a 2-s duration (Edson 2001). Scaling the absorption value for 100 kHz and a more typical 50-ms AAM pulse increases the intensity requirement by a factor of 400 compared with 1 MHz or ~20 MPa (266 dB re 1 μPa^2). Even a much longer pulse of 1 s at 200 kHz would require on the order of 250 dB re 1 μPa^2 to generate a 1 °C rise in tissue. Clearly outside the hearing range of the animal, AAM is completely safe for marine life monitoring.

2 Case Studies

Here we introduce three case studies of AAM of marine life. Although they all serve to detect the presence of marine life to determine behavior, mitigate injury, or both, these examples span different acoustic operating frequencies, utilize different sonar designs, and operate in different environments that illustrate some of the tradeoffs within this space.

2.1 High-Frequency Marine Mammal Monitoring Sonar

The high-frequency marine mammal monitoring (HF/M3) sonar is a 30–40 kHz active sonar system in use aboard the US Navy's surface towed array surveillance low-frequency active (SURTASS LFA) sonar system (Stein et al. 2001a, b). The SURTASS LFA environmental impact statement determined that there was no significant long-term impact to a marine mammal unless it entered the high-pressure area surrounding the array, roughly within 500 m from the transmit array. Thus the HF/M3 sonar system is installed at the top of the towed low-frequency array and scans for marine mammals within 2 km of the ship such that the low-frequency sources can be shut down when marine mammals are detected. The sonar system is composed of four mechanically steered parabolic transducers and is deployed in relatively low-clutter, deep-water environments. This is a mission-critical system that, by permit and court order, must be operational for the Navy to operate the SURTASS LFA system. Figure 138.2a–c, shows the HF/M3 system. Figure 138.2a identifies the SURTASS LFA mitigation zone (green) and the HF/M3 detection zone (yellow), Fig. 138.2b shows the 4 rotating air-backed parabolic transducers that scan the region in roughly 45 s, and Fig. 138.2c shows the display of the HF/M3 system tracking a whale, which resulted in a shutdown of the active operations.

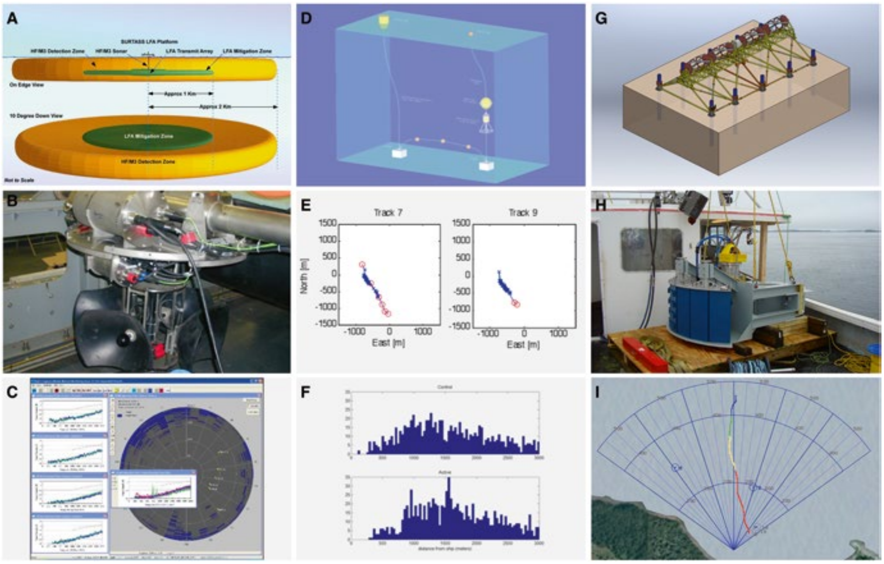

Fig. 138.2 Three cases of active acoustic monitoring of marine life. (**a–c**): High-frequency marine mammal monitoring sonar range, hardware, and operator interface, respectively. (**d–f**): Integrated marine mammal monitoring system deployment, tracking, and approach distribution, respectively. (**g–i**) active acoustic monitoring sonar deployment, hardware, and operator interface, respectively

2.2 Integrated Marine Mammal Monitoring and Protection System

The goal of the integrated marine mammal monitoring and protection system (IMAPS) is to integrate active acoustic detection, passive acoustic detection, radar, and a mitigation management and control module (MMCM; Stein et al. 2009). The MMCM assimilates the available real-time observations, includes a database of marine mammals, and could include an estimation tool for predicting potential harm given the particulars of an operation (source strength, directivity, environmental conditions). Once fully developed, IMAPS would provide a complete decision aid for the user to determine if an operation should continue or be altered.

The active sonar component includes a 60-channel phased-array active sonar. The system was tested during January 2004 and 2008 in the midst of the southbound gray whale migration off the California coast. During the test in January 2008, the active sonar was deployed from an autonomous surface buoy and data were collected without the influence of ship noise. Tracks were then sent on a wireless network to a land-based operation where they were integrated in real time with visual monitoring tracks. During trials in the gray whale migration, it was determined that the animals showed a minor avoidance reaction to active sonar transmitting at ~23 kHz (Frankel 2005). Figure 138.2d–f, shows integrated active acoustic and visual tracks from the 2008

IMAPS experiment. Figure 138.2d shows the IMAPS active phased-array deployment roughly 1 mi off the coast of San Louis Obispo, CA, in January 2008. Data from the active sonar was telemetered to shore and networked with data from two visual observing stations located 1 mi apart on the overlooking bluffs. Figure 138.2e shows integrated sonar (blue) and visual (red) detections forming a track of 2 different gray whales at ranges beyond 500 m. Figure 138.2f shows the distribution of the closest approach to the sonar and indicates a minor avoidance reaction.

2.3 High-Frequency AAM System

The issue of providing underwater port surveillance for threats such as terrorist divers has led to significant advancements in sonar to detect small moving objects in a high clutter environment. Such systems are commercially available (e.g., Sonardyne, Kongsberg). Scientific Solutions, Inc. (SSI), in a joint effort with ORPC Maine, LLC, a subsidiary of Ocean Renewable Power, developed and deployed an active acoustic detection system for marine hydrokinetic (MHK) and other offshore renewable energy projects, specifically for monitoring the region ahead of the tidal turbine. This system was based on SSI's development of the swimmer detection sonar network (SDSN). This system was deployed in Cobscook Bay, ME, in June 2013 in the same regions as the TidGen power system. The goal of the project was to have a monitoring-system design, to have demonstrated the system in a prototype deployment that is integrated with an MHK system, and to be in a position to make it generally available to the MHK and offshore renewable power industry.

This system operates at 90–120 kHz, with ranges out to 500 m, and is designed for tracking larger cetaceans at significant enough ranges to determine the behavioral response. The avoidance reaction from the system for these animals is expected to be minimal because 90–120 kHz is generally above the hearing range of larger cetaceans (Southall et al. 2007). Figure 138.2g–i, shows the system and track obtained from a test target that has roughly the same target strength of a midsize whale. Figure 138.2g shows a tidal turbine deployment in Eastport, ME, Fig. 138.2h shows the AAM sonar, and Fig. 138.2i is an example of the AAM sonar tracking a simulated whale coming in from 500 m.

3 Future Applications and Potential Deployments

AAM can be used to study the behavioral response of marine life and to mitigate harm during high-danger anthropogenic activities. This has been done in fish studies for many decades, and there are now case studies in which AAM has been used for marine mammal monitoring as well. This includes monitoring where the ranges, AAM frequency of operation, and species are such that the AAM operation is completely outside the hearing range of the animals.

However, it also includes AAM operations within the hearing range of marine life, although this does not necessarily imply that AAM is not a suitable tool. Likely the best and most important application of AAM is when the anthropogenic activity to be conducted is temporary and presents a clear danger to the animals. In this case, AAM can provide a definitive "all clear" to conduct or continue the activity and prevent harm. Examples of such activities where AAM absolutely can and should be implemented and used are seismic surveys, explosive removal of offshore structures, and pile driving. In these cases, the AAM systems to be used would certainly present a far lower danger to marine life than the primary activity and perhaps even alert them to stay clear of the area. The technology certainly exists to provide monitoring out to 500 m in most environments and it is only a matter of cost to develop and implement. Experiments to determine, definitively, the response of marine mammals to various AAM systems would be important for implementation and permitting.

This is not to say that AAM cannot also be used to study behavioral responses as was successfully done at short ranges with harbor seals in Strangford Lough, Northern Ireland (Hastie 2012). But, as in that study, the sonar frequency range was chosen along with the resulting detection range to ensure operation out of the hearing range of the species of interest. Indeed, each application of AAM for the study of the behavioral response will likely be species dependent and require a separate study of the behavioral response of the animals to the AAM system alone.

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Chapter 139
Is Sound Exposure Level a Convenient Metric to Characterize Fatiguing Sounds? A Study in Beluga Whales

Alexander Supin, Vladimir Popov, Dmitry Nechaev, Evgenia Sysueva, and Viatcheslav Rozhnov

Abstract Both the level and duration of fatiguing sounds influence temporary threshold shifts (TTSs) in odontocetes. These two parameters were combined into a sound exposure level (SEL). In the beluga whale *Delphinapterus leucas*, TTSs were investigated at various sound pressure level (SPL)-to-duration ratios at a specific SEL. At low SPL-to-duration ratios, the dependence was positive: shorter high-level sounds produced greater TTSs than long low-level sounds of the same SEL. At high SPL-to-duration ratios, the dependence was negative: long low-level sounds produced greater TTSs than short high-level sounds of the same SEL. Thus, the validity of SEL as a metric for fatiguing sound efficiency is limited.

Keywords Temporary threshold shift • Odontocetes

1 Introduction

The impact of noise on the auditory system results in a permanent or temporary reduction in auditory sensitivity; the reductions in sensitivity are known as permanent or temporary threshold shifts (PTSs or TTSs, respectively). Many factors influence TTSs and PTSs in odontocetes, including the spectral content, level, exposure duration, time after exposure, continuous or intermittent manner of exposure, and subject species of the sound. Among these factors, sound level and duration are the most influential; higher levels and/or longer exposure durations produced greater TTS effects. Based on the equal-energy hypothesis (EEH), it was logical to combine these two parameters (i.e., to specify the sound exposure in terms of overall sound energy)

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for the evaluation of the efficiency of fatiguing sounds. This approach has been used in many TTS investigations in odontocetes. Fatiguing sounds have been characterized by their sound exposure level (SEL), which is a decibel measure of the temporal integral of the squared sound pressure level (SPL); SEL is specified as decibels re 1 μPa^2·s. This parameter is an equivalent of a decibel measure of the sound energy flux density (in J/m^2), with the squared sound pressure (in Pa^2) used instead of the power flux density (in W/m^2). The SEL metric has been widely used and is recommended for the characterization of fatiguing sounds (Southall et al. 2007).

However, SEL is not a universal metric for all combinations of SPLs and durations. Investigations of the interaction between SPL and duration in odontocetes have revealed that the dependence of TTS on the SPL of fatiguing sound becomes steeper as the sound duration increases, and, conversely, the dependence of TTS on duration becomes steeper as the SPL increases. These regularities were summarized by a model that implied that TTS is the product of the TTS versus SPL and TTS versus log duration functions (Finneran et al. 2010). If the duration-dependent TTS growth depends on the fatiguing sound level and, conversely, the level-dependent TTS growth depends on fatiguing sound duration, then the time-intensity trade-off may be either lower or higher than 1 dB/dB, which contradicts the EEH.

Indeed, available data have demonstrated different (either positive or negative) manners of TTS dependence on the SPL-to-duration ratio of the fatiguing sound (Nachtigall et al. 2003; Finneran et al. 2007; Mooney et al. 2009; Popov et al. 2011, 2013). However, a few independent observations do not compose the whole picture of the dependence of TTS on the SPL-to-duration ratio. For a more complete understanding of how the SPL-to-duration ratio influences TTSs in odontocetes, a more systematic investigation of various combinations of these two parameters is necessary; this is the goal of the present study. In this study, the auditory evoked potential (AEP) method was used to measure hearing thresholds and shifts in those thresholds (i.e., TTSs) because this method is convenient, is not time consuming, and does not require prior training of the subject.

2 Materials and Methods

The study was conducted in the facilities of the Utrish Marine Station of the Russian Academy of Sciences (the Black Sea coast). The subject was a 2-year-old female beluga whale (*Delphinapterus leucas*). The animal was housed in a 9 × 4 × 1.2-m pool filled with seawater. During the experiments, the animal was placed on a stretcher in a wooden tank 4.5 × 0.85 × 0.6 m filled with seawater in such a manner that the dorsal surface of the head and the blowhole remained above the surface of the water.

Suction-cup electrodes were used for AEP recording. The active electrode was fixed at the vertex of the head's surface, 7 cm behind the blowhole and above the surface of the water, and the reference electrode was fixed at the back. The electrodes were connected, via shielded cables, to the input of a custom-made EEG amplifier that provided an 80-dB gain within the frequency range of 200 to 5,000 Hz.

The amplified signal was digitized and collected using a DAQcard-6062E data-acquisition board (National Instruments) and stored in computer memory.

The test sound stimuli were trains of tone pips. Each train contained 16 pips at a rate of 1,000 pips/s. Each pip of the train contained 8 cycles of 32-kHz carrier enveloped by a cosine function; thus, the pip duration was 0.25 ms. The pip trains were presented at a rate of 16 trains/s. The SPL of the pip trains was specified in decibels re 1 μPa of root-mean-square (rms) sound pressure over the 16-ms pip-train duration.

The fatiguing noise was a half-octave band-filtered noise with a center frequency of 22.5 kHz. The SPL of the noise was specified in decibels re 1 μPa of rms sound pressure.

Both the test and fatiguing sounds were digitally synthesized at a sample rate of 512 kHz and were digital-to-analog converted by the same DAQcard-6062E board, amplified, attenuated, and played through an ITC-1032 (International Transducer Corporation) transducer. The transducer was positioned 1 m in front of the animal's head. To amplify and attenuate the test signal, a custom-made amplifier-attenuator with a 200-kHz passband was used. To amplify the fatiguing sound, a CV-1800 amplifier (Cervin Vega) with a 65-kHz passband was used. The playback channel was calibrated before and after the experiments by positioning a calibrated receiving hydrophone (B&K 8,103, Bruel & Kjaer) near the animal's head.

For AEP recording, 25-ms sweeps that were synchronous with the test stimuli were extracted from the brain-potential records. Five hundred sweeps that were triggered by the stimulus onset were coherently averaged online. For further analysis, a 16-ms segment of the averaged record (from 5th to 21st ms relative to the stimulus onset) containing a rhythmic AEP (the envelope following response [EFR]) evoked by the pip-train stimulus was Fourier transformed online to obtain the response-frequency spectrum. The magnitude of the 1-kHz spectral peak was taken as the measure of response magnitude.

Both the pre- and postexposure threshold dynamics were traced using an adaptive one-up one-down staircase procedure of stimulus variation. A record was considered to be response-present when the 1-kHz peak in the response spectrum was more than twice the magnitude of the spectrum components within the adjacent spectrum between 0.75 and 1.25 kHz; otherwise, the record was considered to be response-absent. Stimulus levels were varied in 5-dB increments/decrements. If a response was detected according to the criterion specified above, the subsequent stimulus level was decremented by 5 dB; if the averaged record was response-absent, the subsequent stimulus was incremented by 5 dB. Reversal points (transitions from stimulus level increases to decreases and vice versa) were selected, and the mean of each pair of adjacent reversal points (the local maximum and minimum) was assigned as an instant threshold estimate attributed to the middle point of the two corresponding time instants.

Fatiguing noise levels varied from 155 to 170 dB re 1 μPa. Exposure durations varied from 19 to 6,000 s. Postexposure thresholds were traced for no longer than 1 h, even if the total recovery was not achieved. No disturbances of the animal's behavior were observed on its return into the home pool.

3 Results

Pip trains used as test stimuli provoked EFRs that consisted of bursts of waves at the same frequency as the stimulus pip rate. In the majority of cases, a single 5-dB increment (or decrement) resulted in a transition from a response-absent to response-present (or vice versa) record when stimulus levels were varied in the range near the threshold (as determined by the adaptive procedure). In some cases, this transition required changing the stimulus level by two steps (10 dB). Baseline threshold measured according to the procedure described above (see Section 2) was evaluated as 52.5 dB re 1 μPa.

Immediately after exposure to fatiguing noise, the thresholds increased relative to the preexposure (baseline) threshold and gradually recovered thereafter. The threshold versus time functions could be satisfactorily (R^2 from 0.91 to 0.98) approximated with log regression lines. Postexposure thresholds were estimated as the values of these log regression lines at 2 min after offset of the fatiguing noise (that was the time sufficient for a threshold measurement). The difference between the post- and preexposure thresholds was taken as the TTS.

All combinations of fatiguing noise SPLs from 155 to 170 dB re 1 μPa (5-dB increments) and durations from 19 to 6,000 s (by 3.2-fold increments) were tested. The only exception was the combination of the highest SPL (170 dB) and the longest duration (6,000 s); the animal was not exposed to this combination for safety reasons. The results demonstrated monotonic increases in TTS with increases in both the SPL and duration of the fatiguing sound (Fig. 139.1). Both the TTS versus log duration and TTS versus SPL dependences were satisfactorily approximated by regression lines (R^2 from 0.80 to 1.0 and from 0.91 to 0.99, respectively).

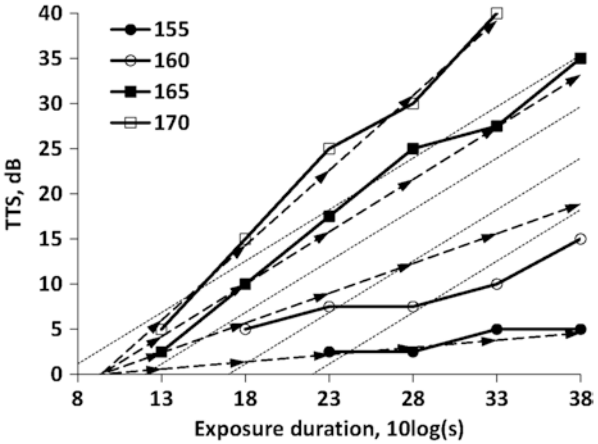

Fig. 139.1 The dependence of temporary threshold shift (TTS) on the fatiguing noise duration with sound pressure level (SPL; in dB re 1 μPa) as a parameter. *Straight dotted lines* represent the approximations of the data produced by the equal-energy model. *Straight dashed lines with arrowheads* represent the approximations of data produced by the multiplication model (both approximation methods employed the least-mean-square criterion)

The slope of the TTS versus duration increased as SPL increased (Fig. 139.1a), and the TTS versus SPL functions increased with increasing exposure durations. Regression lines fitted to the TTS versus duration functions exhibited slopes (±SE) that ranged from 3.0 ± 0.2 dB per log unit for the 155-dB SPL to 17.0 ± 1.0 dB per log unit for the 170-dB SPL. The TTS versus SPL functions featured slopes that ranged from 0.40 ± 0.14 dB/dB for the 19-s duration to 2.75 ± 1.01 dB/dB for the 6,000-s duration. For all sound durations, the TTS versus SPL functions fell to 0 TTS at a SPL of 154–155 dB re 1 μPa. The TTS versus duration functions fell to 0 TTS at durations of 6–16 s.

The same dataset was used to characterize the dependence of TTSs on SPL-to-durations ratios of a fatiguing sound at a particular SEL. In Fig. 139.2, TTS is plotted as a function of the SPL-to-duration ratio while the SELs were kept constant. The SPL-to-duration ratio is presented as decibel measure R, which is the difference between the SPL (in dB) and a decibel measure of duration T (in s)

$$R = \mathrm{SPL} - 10\log T \tag{139.1}$$

If SPL is specified in decibels re 1 μPa and T is specified in seconds, R is specified in decibels re 1 $\mu\mathrm{Pa}^2\cdot\mathrm{s}$.

The presentation of the data in Fig. 139.2 shows that keeping SEL constant did not result in constant TTSs over varying SPL-to-duration ratios. The dependence of TTS on the SPL-to-duration ratio R was nonmonotonic. At low R values, the TTS versus R dependence was positive; greater SPL-to-duration ratios resulted in greater TTSs when the SEL was kept constant. At high R values, this relationship was negative; greater SPL-to-duration ratios resulted in lower TTSs. The positive-to-negative inflection points occurred at SPL-to-duration ratios ranging from 143 dB (at a SEL of 188 dB re 1 $\mu\mathrm{Pa}^2\cdot\mathrm{s}$) to 148 dB (at a SEL of 183 dB re 1 $\mu\mathrm{Pa}^2\cdot\mathrm{s}$), i.e., the inflection points occurred within the intermediate range of the SPL-to-duration ratios.

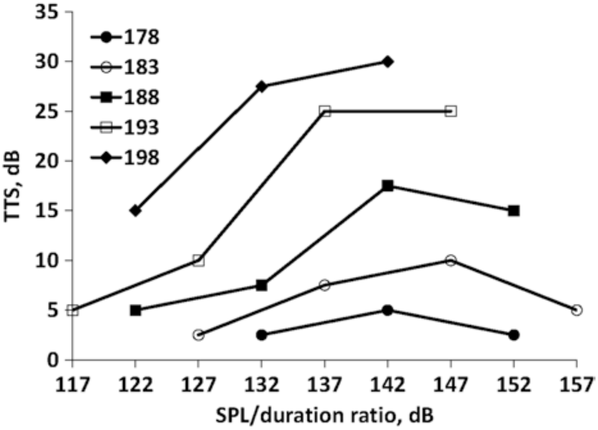

Fig. 139.2 The dependence of TTS on the SPL-to-duration ratio with sound exposure level (SEL; in dB re 1 $\mu\mathrm{Pa}^2\cdot\mathrm{s}$) as a parameter

Notably, at effective SPL-to-duration ratios, greater TTSs were produced by lower SELs than by higher SELs at ineffective intensity-to-duration ratios.

4 Discussion

The data presented herein allow for comparison with various models of the dependence of TTS on fatiguing sound intensity and duration: the equal-energy model and the multiplication model. The equal-energy model can be presented by the following equation

$$\mathrm{TTS} = k\left(\mathrm{SPL} + 10\log T - \mathrm{SEL}_0\right) \tag{139.2}$$

where TTS is expressed in decibels, T (in s) is duration of the sound, SEL_0 (in dB re 1 μPa^2·s) is the minimum SEL to produce any TTS, and k (in dB/dB) is a factor that determines the TTS value. The multiplication model was presented by an equation

$$\mathrm{TTS} = k\left(\mathrm{SPL} - \mathrm{SPL}_0\right)\cdot 10\left(\log T - \log T_0\right) \tag{139.3}$$

where SPL_0 (in dB re 1 μPa) and T_0 (in s) are the minimal SPL and duration that produce any TTS, respectively. The data were approximated with these two models, and the results are presented in Fig. 139.1. The equal-energy model produced a worse fit to the experimental data than the multiplication model (i.e., the approximating straight lines of the equal-energy model deviated farther from the experimental plots than did the lines produced by the multiplication model). For the equal-energy model, the least-mean-square disagreement achieved by iterative adjustment of the parameters was 6.2 dB; for the multiplication model, the least-mean-square disagreement was 1.8 dB.

The multiplication model implies TTS is not constant for a constant SEL. In accordance with this prediction, the data demonstrated substantial SPL-to-duration ratio-dependent variation in TTS when the SEL was kept constant and thus indicate deviation from a complete (equal-energy) time-intensity trade. Therefore, adequate characterization of fatiguing sounds requires a more complicated approach that cannot be based on SEL alone.

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Chapter 140
Frequency Tuning of Hearing in the Beluga Whale

Evgeniya V. Sysueva, Dmitry I. Nechaev, Vladimir V. Popov, and Alexander Y. Supin

Abstract Data on frequency tuning in odontocetes are contradictory: different authors have reported filter qualities from 2 to almost 50. In this study, frequency tuning was measured in a beluga whale (*Delphinapterus leucas*) using a rippled-noise test stimulus in conjunction with the auditory evoked potential (AEP) technique. The response to ripple reversions was considered to indicate resolvability of the ripple pattern. The limit of ripple-pattern resolution ranged from 20 to 32 ripples per octave (rpo). A model of interaction of the ripple spectrum with frequency-tuned filters suggests that this resolution limit requires a filter quality of 29–46.

Keywords Toothed whales • Ripple spectrum • Auditory evoked potentials

1 Introduction

The auditory system of odontocetes (toothed whales, dolphins, and porpoises) have unique capacities (Au 1992; Supin et al. 2001; Au and Hastings 2008), a high sensitivity (thresholds down to 10^{-14} W/m^2 vs. 10^{-12} W/m^2 in humans), and a wide frequency range (>100 kHz, reaching almost 200 kHz in some species, vs. 15–20 kHz in humans) being the most commonly known. Less is known about the discriminative capacity of hearing, specifically, frequency tuning, in odontocetes. Several attempts at estimating the frequency tuning in odontocetes on the basis of different experimental paradigms have been made.

In behavioral experiments, several paradigms were used: critical ratios (Johnson 1968; Johnson et al. 1989; Au and Moore 1990; Thomas et al. 1990; Kastelein et al. 2009; Lemonds et al. 2011), critical bands (Au and Moore 1990), tone-tone masking (Johnson 1971), and notch-noise masking (Finneran et al. 2002; Lemonds et al. 2012). In these studies, low values of auditory filter quality (*Q*) were obtained, which were

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close to those in terrestrial mammals, including humans, but significantly lower than those in bats (Fay 1988).

Auditory evoked potential (AEP) studies combined with tone-tone masking in 5 species of toothed whales showed *Q* varying from 30 to 50 in the high-frequency range of hearing (Supin et al. 1993, 2001; Popov et al. 1996, 2006; Popov and Klishin 1998; Klishin et al. 2000). The notch-noise masking in combination with the AEP method (Popov et al. 1997) also showed acute frequency selectivity in the bottlenose dolphin (*Q* varying from 35 to 36). Thus, there is a significant difference between the frequency selectivity estimates obtained by different methods.

The experiments mentioned above used masking methods. Another test employed noise with a ripple spectrum (rippled noise), which directly reveals the ability of the auditory system to discriminate fine spectrum patterns: the finer the resolvable spectrum pattern (i.e., the higher the ripple density), the better the frequency resolution. Wideband and narrowband rippled spectra were used in behavioral studies (Au and Pawloski 1989; Supin et al. 1992; Tarakanov et al. 1996). Supin et al. (1992) and Tarakanov et al. (1996) used a rippled-noise probe in combination with the ripple-phase reversal test, which was earlier suggested for psychoacoustical studies (Supin et al. 1994, 1998). The results of measurements in the bottlenose dolphin were presented in terms of relative ripple density, which is an inverse of relative ripple spacing. When presented in terms of this metric, the ripple-density resolution varied from 7.0 at a frequency of 2 kHz to 48.3 at 128 kHz. As a first approximation, it was assumed that the ripple-pattern resolution limit is quantitatively equal to the *Q* of the frequency-tuned filter; thus, the results indicated that *Q* varied from 7 at low frequencies to almost 50 at high frequencies.

The AEP technique has been also applied to frequency-tuning measurements with the use of the rippled-noise test (Supin and Popov 1990). Experiments with middle-latency AEPs demonstrated a resolution of ripple patterns as high as 25–30 for frequencies of 64–128 kHz; at lower frequencies, the resolvable ripple density decreased to 4 for a frequency of 8 kHz.

The goal of the present study was to analyze frequency tuning in odontocetes in more detail. Among the experimental paradigms mentioned above, we chose the ripple-spectrum test. In previous studies with the use of this test, analogous techniques of signal generation provided poor signal control. Here, we used a digital signal-generation technique in combination with the AEP method, specifically, auditory brainstem response (ABR) recording.

2 Materials and Methods

2.1 Subject and Experimental Conditions

Experiments were performed on a 2-year-old male beluga whale in the Utrish Marine Station of The Russian Academy of Sciences (the Black Sea coast). During the experiments, the whale was placed in a 9- × 4- × 1.2-m wooden pool filled with seawater so that the dorsal surface of the head and the blowhole were above the water surface. The duration of 1 experimental session was 2–3 h.

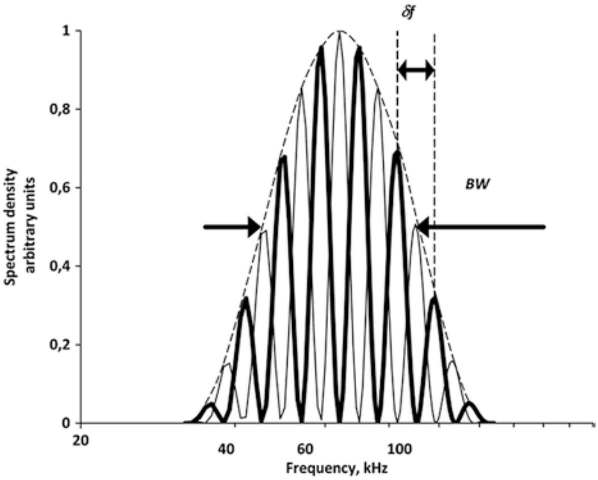

Fig. 140.1 Rippled spectrum of the test stimulus. A spectrum of a 64-kHz center frequency and a ripple density of 4 ripples/octave is exemplified. *Thick and thin lines*, spectra of alternative ripple phases; dashed line, spectrum envelope. BW, spectrum equivalent rectangular bandwidth (ERB); Δ*f*, ripple-frequency spacing

2.2 Test Stimulus

Band-limited rippled noise was used as a stimulus. The envelope of the noise spectrum was a 2-octave cycle of cosine function, with ripples as a cosine function of the frequency logarithm within the envelope. The ripples of this pattern were frequency proportional, i.e., the ripple spacing (Δ*f* in Fig. 140.1) throughout the passband was a constant proportion of the ripple peak frequency. A convenient metric for this type of ripple is the number of ripples per octave (rpo).

To estimate the ability to discriminate ripple patterns, the ripple-phase reversal test was used. In this test, a rippled noise was replaced by a noise with the opposite position of ripple peaks and troughs, with the other parameters of the signal remaining constant. It was assumed that these changes provoke AEPs only if the ripple pattern is recognized by the auditory system.

Two types of stimulation were used: single-phase reversals and multiple rhythmic-phase reversals. In the first type, rippled noise was presented for 10–30 ms, after which it was replaced with noise with the opposite position of ripples. At the moment of reversal, a triggering pulse was generated in a separate channel. This pulse triggered the AEP recording. During the recording, each stimulus was generated online; thus, random fluctuations intrinsic in noise did not repeat from stimulus to stimulus. The pretriggering noise duration varied randomly within a range of 10–30 ms; therefore, late AEP components provoked by the noise onset were not coherently averaged and recorded.

The rhythmic-phase reversal stimulus contained 20 phase reversals at a rate of 1,000/s. This rate efficiently provoked a rhythmic AEP sequence (the envelope following response [EFR]). The overall duration of the stimulus was 20 ms.

The central frequency of the noise varied from 32 to 90 kHz. The intensity of the stimulus was 40 dB above the threshold.

Test signals were digitally generated and converted to analog by a 16-bit digital-to-analog converter of a DAQ card6062 board (National Instruments). The analog signals were amplified, attenuated, and played back through either an ITC-1032 transducer for frequencies from 32 to 45 kHz or a Brüel & Kjær 8,104 transducer for frequencies from 64 to 90 kHz. The transducer was placed 1 m in front of the animal's head. A Brüel & Kjær 8,103 hydrophone was used to monitor the sound pressure level near the animal's head before and after the experiment. The monitoring revealed that despite the sound reflections within the tank, the local sound levels around the animal's head varied within a range of <5 dB.

2.3 Evoked-Potential Registration

For noninvasive detection of the evoked potentials, suction-cup electrodes were used. They consisted of a 15-mm stainless steel disk mounted within a 60-mm silicon suction cup. The active electrode was fixed at the top of the head surface 7 cm behind the blowhole, above the water surface. The reference electrode was fixed at the back of the animal, also above the water surface.

The signals from the electrodes were amplified and digitized by a 16-bit analog-to-digital converter of the DAQ card6062 board. Windows (15–25 ms) triggered synchronously with the test stimuli were extracted from the brain potential recordings, and 500–1,000 sweeps were averaged online.

The response to a single-phase reversal stimulus was detected by the peak-to-peak amplitudes of the averaged recording within a window of 3.5–7 ms after it was triggered. To assess the standard error (SE) of the recordings, the root-mean-square (rms) value was measured in control recordings (without stimuli) obtained with the same number of averaged sweeps. Amplitudes less than ±1.96 (SD; 95% probability interval) were considered not significant.

The magnitude of responses to rhythmic-phase reversals was estimated on the basis of the frequency spectrum of the recording. A 16-ms segment of the recording containing EFR but without an on-response to the noise onset was Fourier transformed. The height of the spectral peak at the ripple reversal frequency (1 kHz) was taken as a measure of the response magnitude. The mean value of the spectral component around this peak (0.75–1.25 kHz) was taken as the noise floor of the spectrum. The 1-kHz component exceeding this floor by a factor of <1.96 was considered not significant.

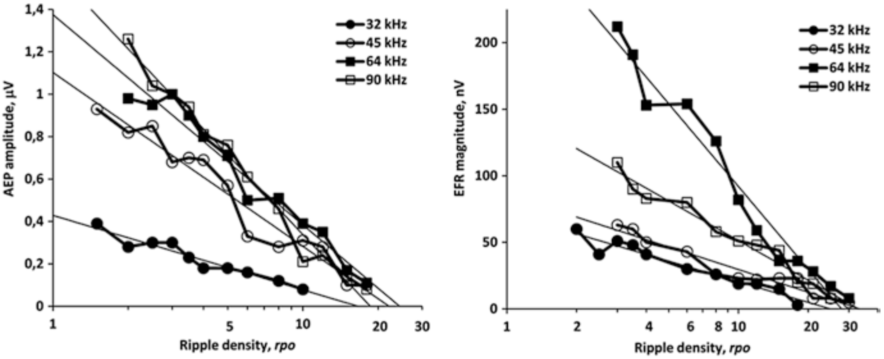

Fig. 140.2 (**a**) Auditory evoked potential (AEP) amplitude dependence on ripple density (rpo). Center frequencies of the test stimuli are indicated. *Solid lines* are approximations of AEP dependence on rippled density by log regression (R^2 from 0.95 to 0.98). (**b**) Envelope following response (EFR) magnitude dependence on ripple density. Center frequencies of the test stimuli are indicated. *Solid lines* are approximations of EFR magnitude dependence on rippled density by log regression (R^2 from 0.95 to 0.98)

3 Results

3.1 Single-Phase Reversal Test

This test provoked AEPs with a latency of 3.5 ms and a duration of 3.5–4.5 ms. The AEP amplitude depended on the ripple density when other parameters of stimuli remained constant. The responses were maximum at low densities (2–3 rpo); an increase in the ripple density led to a decrease in the AEP amplitude. There was no AEP when the rippled density was 18 rpo or higher. The AEP amplitude also depended on the center frequency of the noise band. The amplitude was highest at high frequencies (64–90 kHz) and lower at a lower frequency (32 kHz). The amplitude dependence on both the center frequency and ripple density is shown in Fig. 140.2a. The upper limit of ripple resolution varied from 17 rpo at 32 kHz to 24 rpo at 64 kHz.

3.2 Multiple Rhythmic-Phase Reversal Test

The response to rhythmic ripple reversals consisted of two components. The first one was the response to the noise onset and looked like a typical ABR. The second component was an EFR, a rhythmic wave sequence with a frequency of 1,000 Hz (the frequency of ripple reversal) lasting as long as the rippled-noise burst did. The EFR magnitude depended on the ripple density: the higher the density, the lower the EFR magnitude as estimated by the 1-kHz spectrum component. The highest amplitude was observed at high center frequencies and decreased with a decreasing center frequency of the stimulus. The amplitude dependence on both the stimulus center frequency and ripple density is shown in Fig. 140.2b. This method revealed a higher ripple resolution than the single reversal test: from 20 rpo at 32 kHz to 32 rpo at 45–90 kHz.

4 Discussion

To compare the results of this study with earlier published data, it is necessary to recalculate the ripple-density resolution to the filter quality. This can be made using a simple model based on the excitation pattern (the excitation level as a function of frequency representation within the auditory system) computed as a convolution of the stimulus spectrum and the filter form. As an idealized filter form, we used the rounded exponential function (roex), which was suggested as an empirical formula for human auditory filters (Patterson et al. 1982; Patterson and Moore 1986) and has been successfully used for filter form approximation in odontocetes (Popov et al. 1997, 2006; Finneran et al. 2002; Lemonds et al. 2012)

$$W(g) = (1 + pg)e^{-pg}$$

where $W(g)$ is the filter form, p is a parameter determining the filter quality, and g is the normalized deviation from the filter center frequency. The equivalent rectangular bandwidth (ERB) of this filter is $4/p$.

For this filter form, the ripple-density resolutions from 20 to 32 rpo correspond to filter bandwidths from 1/20 to 1/32 octave. These values can be converted into Q using the equation

$$Q = 1/\left(2^{W_{oct}/2} - 2^{-W_{oct}/2}\right) = 1/\left(2^{1/2D} - 2^{-1/2D}\right)$$

where D is the ripple density (in rpo) and W is the filter bandwidth in octave measure (oct). Assuming that the threshold ripple width is equal to the filter ERB, the ripple-density resolutions from 20 to 30 rpo correspond to Q from 29 to 46 or ERB from 3.4 to 2.2% of the center frequency.

Thus, the Q obtained in this study is substantially higher than in several behavioral experiments, where this value was ~10 (Johnson 1968), 2.2 (Au and Moore 1990), or 8.5–5.9 (Finneran et al. 2002) in the bottlenose dolphin and 11.0–6.5 (Finneran et al. 2002) or 5.9–8.8 (Lemonds et al. 2012) in the beluga whale. However, our data agree with the results of behavioral studies by Supin et al. (1992) and Tarakanov et al. (1996) on the beluga whale, where Q was 48.3 in the high-frequency area. The results of our study are also close to the Q values of 30–35 reported for bottlenose dolphins (Supin et al. 1993; Popov et al. 1996, 1997, 2006; Popov and Klishin 1998), about 50 found in belugas (Supin et al. 1992; Klishin et al. 2000), and 45–47 found in harbor porpoises (Popov et al. 2006).

It should be noted that echolocation of odontocetes is characterized by a very high frequency resolution. A bottlenose dolphin was able to discriminate echoes with a rippled spectrum when the ripple patterns were shifted by 3.3 kHz at frequencies above 100 kHz and by 3.9 kHz at frequencies above 160 kHz, i.e., by 2.5 and 3.3%, respectively (Au 1992). This resolution requires a filter Q range of 30–40. These estimates agree entirely with those obtained in our study.

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Chapter 141
How Might We Assess and Manage the Effects of Underwater Noise on Populations of Marine Animals?

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Abstract The European Union Marine Strategy Framework Directive (MSFD) aims to achieve good environmental status (GES) in European seas by 2020. One of the features of GES is that underwater sound should not adversely affect the marine environment. Direct injury of marine life may occur, but a more pervasive effect is likely to be through the cumulative indirect effects on behavior. Assessing the significance of these effects on an ecosystem scale is difficult. If subsequent management of these effects is required, complex and challenging international decisions will be required.

Keywords Cumulative impact • Management • Harbor porpoise

1 Background

Impulsive low- and midfrequency sound is known to have adverse effects on marine organisms and therefore has the potential to affect the environmental status of European seas. It is therefore one of the first sound types being assessed under the European Union (EU) Marine Strategy Framework Directive (MSFD). Such sounds derive from human activities such as pile driving and seismic survey. At close range, these sounds could cause physical or physiological damage to organisms, although it is believed that the response by organisms, mitigation, and the relative rarity of these sounds will minimize the direct risk of population-level effects. One of the responses is for organisms to move away from such sounds, potentially creating broad-scale gaps in the distribution of populations. Such gaps could reduce the carrying capacity of the overall environment. Modeling is needed to understand when such gaps might become significant.

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Modeling will also be needed to add in other anthropogenic factors affecting populations, including from the second source of noise being assessed under the MSFD, low-frequency continuous sound, so as to ensure that this pressure on the environment does not compromise the ability of populations of marine species to achieve good environmental status. Ultimately, such modeling might lead to management measures to avoid significant effects and the real challenge then is likely to be balancing the management of the various human pressures.

There have been very few field studies of behavioral disturbance of marine organisms, mostly due to the difficulties of tracking animals that spend their time largely out-of-sight underwater. Studies have been undertaken on the harbor porpoise *Phocoena phocoena* using both surface sightings and underwater vocalizations. It is widely believed that harbor porpoises are one of the animals most sensitive to disturbance; thus studies and measures based on their behavior are likely to be precautionary when applied to other organisms.

2 Assessing Occurrence of Potentially Disturbing Activities

Several European countries are responding to the need to assess impulsive low- and midfrequency sound by establishing a noise register. These registers might be viewed as a record of the data needed to create broad-scale maps of the location of activities that generate noise; Tasker et al. (2010) recommended using a spatial scale of ~10 nautical miles (16 km) × 6 nautical miles (11 km), with a temporal scale of a day; this is a pragmatic selection based on the units of sea used in the process of licensing for hydrocarbon exploration and approximately on the same order of magnitude of area and time over which harbor porpoises have been observed as being affected by a loud impulsive sound. Studies have occurred around marine wind farms being installed using pile drivers. Tougaard et al. (2009) studied the reactions of harbor porpoises to pile driving at Horns Reef to the west of Jutland. Reactions were evident at distances beyond 21 km from the site. Porpoises apparently returned to the affected area within a few hours of the end of each pile-driving event. In the same area, Brandt et al. (2011) showed the effects on harbor porpoises at 18 km distance but not at 21 km, but the timing of return (1–3 days) was longer. Two studies off Germany (Brandt et al. 2012; Dähne et al. 2013) gave comparable reaction distances of ~20 km, with a return time of ~16 h. Braasch et al. (2013) also found reaction distances of ~18 km.

Tougaard et al. (2013) reviewed these and other relevant studies and based on a number of worst-case assumptions, considered it likely that pile driving on its own in the UK sector of the North Sea will have only a minor negative impact on the harbor porpoise population in the next decade. The probability and severity of such negative impacts depends, though, on the spatial and temporal association between activities and porpoise habitat and distribution, which is impossible to predict with any great certainty given the free-ranging nature of these animals, the continually changing nature of their environment (also difficult to predict), and the spatially and temporally variable intensity of the pile-driving operations.

3 Cumulative Effects

Pile driving for wind farms is only one of the activities that can displace harbor porpoises (and other organisms). Pile driving can occur for other marine and coastal construction. Seismic exploration using air guns occurs on virtually every day of the year in the North Sea, with multiple surveys in different areas common in the calmer summer months. Although no specific study of displacement has been published, work by Thompson et al. (2012) indicates no broad-scale displacement of these animals from a seismic survey area off the east coast of Scotland, although further analyses were needed to investigate whether displacement occurred at finer temporal and spatial scales. Stone and Tasker (2006) found that extremely few harbor porpoises were observed from seismic vessels that were firing air guns compared with times when the same vessels were not firing the air guns. It would be reasonable to assume that the same scale of displacement is occurring from this sound source that occurs from pile driving, although temporal surveys may be continuous over a number of days and spread over a wider area. There is some evidence that ships can displace harbor porpoises at least temporarily, so in areas of high shipping density, this effect may continue beyond the passage of a single ship. Knowledge of the location of industrial activities can be gained from national permitting systems while shipping can be plotted using the automatic identification system (AIS) for ship monitoring. It should thus be possible to map activities likely to disturb harbor porpoises and provide some indication of the duration and persistence of those activities.

4 Limits to Effects

The cumulative effect of all these activities will be to displace harbor porpoises from a proportion of their habitat, although that proportion will change in both size and location over time. This displacement essentially reduces the amount of habitat available for the harbor porpoise population and if the disturbance persists, the overall carrying capacity of the sea. Whether such loss of carrying capacity is important is a societal judgment. No marine environment is pristine (unaffected by human activity) and the carrying capacity of most environments has been reduced already. In the case of harbor porpoises, targets have been set under the Agreement on the Conservation of Small Cetaceans of the Baltic, Northeast Atlantic, Irish, and North Seas (ASCOBANS) to strive toward achieving 80% of carrying capacity over a long-time horizon. This figure was set in the context of lethal bycatch of the species. On the basis of this and a variety of assumptions about the vital rates of porpoises, it is possible to calculate that no more than 1.7% of the best estimate of the population abundance may be killed in fishing nets in any year. There is no evidence and it seems unlikely that disturbance will directly kill harbor porpoises, but a loss of overall carrying capacity is likely to exhibit itself in population terms through a degradation of one of the vital rates (e.g., birth rate, mortality) of the animal.

As far as is known, no process has reached a decision on the disturbance limits for harbor porpoises (or other marine organism) anywhere in European seas. It is possible to envisage a limit to disturbance being set, and it would be useful to consider the consequences and identify what other considerations might then be needed. Plainly, a first step is to reduce as much as possible the amount of sound being emitted, but there will be practical limits to this. For example, there are no fully proven ways of replacing air gun arrays in use for seismic survey, so if society still wishes to find new hydrocarbon resources, noise from air guns will continue to occur. Further research and technical development toward a reduction in sound inputs should be encouraged. Alongside this, it may be necessary to develop a workable and pragmatic means to limit disturbance.

5 Thoughts on Regulation

It is uncommon for all marine activities to be regulated by the same body, so an early challenge would be to get the various regulators to work together to gain agreement on a common way of approaching the issue. Because both sound and marine life take little notice of international marine boundaries, there would need to be international agreement on this approach in seas with multiple coastal states. A start to this comes in EU waters from the MSFD where the establishment of national and, in due course, international noise registers is occurring. Noise registers at least allow all regulators to see where the noise is occurring (and has occurred) in a common framework. Should noise input need to be limited, registers would give a foundation for decision making.

If there are limits on disturbance, it would plainly not be helpful for any one activity to use a disproportionate amount of the allowance to the disadvantage of other activities. An analogy might be fish harvesting, where a common resource (the fish stock) is shared out as harvesting opportunities to the fishing industry. In some cases, there is direct trading of these shares of the quota, whereas in other cases, swapping may occur. Perhaps a better analogy might be the carbon markets that have been established in an effort to limit or reduce the amount of carbon emissions into the atmosphere. Could there be a market in permission to emit sound? Such a system should reward those activities that reduce their sound output, but a market system may prove administratively costly to establish and operate. Another system might be to levy a fee for noise (in a similar way to the use of a levy to reduce pesticide use). A levy could pay for the regulatory regimen, including studies to gain better ecological understanding (cf. toxicity testing), and for research into better technology (more precise pesticides). Levies would act as incentives to innovate.

As noted earlier, many other activities can affect marine life. One way of mitigating the potential population effects of disturbance might be to reduce other pressures on marine life. For example, accidental capture of cetaceans in fishing nets very often leads to the animals' death. Could further efforts to reduce bycatch be used to offset the effects of disturbance? Compensatory measures are often used in environmental management to offset adverse effects when other mitigation options are not feasible or there are residual effects. Bycatch remains the single most important threat to harbor porpoises in European waters.

6 A Possible Framework

The debates around this topic are needed soon; we do not know (nor may we ever know) what is "too much" disturbance, and as noted above, this is as much a societal as a scientific choice. Should further regulation be required, particularly to address the cumulative impacts, possible ways forward also need to be considered. A possible framework might consist of (1) an (international) noise register covering areas of the sea that should ideally be managed as one. This would hold information on planned and completed activities that would look both ahead and retrospectively. Such work is under way under the MSFD, but a substantial effort is still required to complete it; (2) further modeling to examine scenarios of disturbance and its consequences. Modeling could use a carrying-capacity approach (Tougaard et al. 2013) that would allow the impact of bycatch to be included or could use a population consequences of disturbance approach (Harwood et al. 2014); (3) absolute abundance estimates to have the context of population numbers within biologically supportable management units; (4) triggers for limits to be considered. Possibly, a development/activity could be limited to the use of a low percentage of overall "allowable noise disturbance"; and (5) a decision-making mechanism. Choices may vary between nations, but if collectively we are to safeguard a common heritage, then some compromises will be needed.

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Chapter 142
Anthropogenic Noise and Physiological Stress in Wildlife

Jennifer B. Tennessen, Susan E. Parks, and Tracy L. Langkilde

Abstract The ecological impacts of increasing levels of anthropogenic noise in marine and freshwater systems are of growing public interest. Recent emphasis on the physiological approaches to identifying the impacts of noise has led to increased recognition that anthropogenic noise is an environmental stressor. We briefly review the research on noise-induced physiological stress. Additionally, we summarize findings from a controlled playback experiment that explored the relationship between traffic noise and physiological stress in anurans (frogs and toads), an aquatic group that relies on acoustic communication for survival and reproduction.

Keywords Noise • Stress • Corticosterone • Glucocorticoid • Frog

1 Introduction

Noise from human activities in aquatic environments is widespread and affects wildlife in many ways. Understanding the behavioral responses of wildlife to noise has been the focus of several decades of important work that has revealed a variety of compensation, evasion, and alteration responses that animals employ to mitigate or minimize noise impacts (e.g., Popper 2003; Brumm and Slabbekoorn 2005; Nowacek et al. 2007). Despite insights into behavioral responses, the sublethal consequences of noise exposure for nonhuman animals remain poorly understood. Abundant evidence shows that chronic anthropogenic noise affects human health (e.g., Babisch 2000; Ouis 2001; Öhrström et al. 2006). Thus, it is critical to understand whether and how noise affects wildlife similarly and identify the population-level impacts of the sublethal consequences of noise.

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We provide a brief review of one potential sublethal impact of anthropogenic noise on wildlife, that of physiological stress. We first provide an introduction to the vertebrate physiological stress response and the consequences of exposure to chronic stress, confining our focus specifically to glucocorticoid production. Next, we briefly discuss our research on the effects of road noise on wood frog stress levels. Finally, we conclude with suggestions for future directions that would make substantial contributions to work in this field.

2 The Physiological Stress Response

Despite the incredible diversity among animals, the vertebrate response to environmental stressors has been highly conserved across taxa (Wingfield et al. 1998; Romero 2004) and has evolved to minimize the negative physiological effects of stressors (Romero 2004). Such stressors can include those of natural origins, such as predation, drought, or social hierarchy (Romero 2004), or anthropogenic stressors such as pollution and habitat loss (Relyea and Mills 2001; Janin et al. 2011). In response to such stressors, the hypothalamus triggers a cascade of hormone release that ultimately stimulates glucocorticoid secretion by the adrenal/interrenal cortex. Glucocorticoids play several roles that collectively help the body prepare for and respond to the stressor (Sapolsky et al. 2000; Romero 2004), including the mobilization of energy stores and suppression of unnecessary activities. Consequently, the secondary stress response is an adaptive response that helps the body achieve allostasis (McEwen and Wingfield 2003).

Elevated levels of corticosterone are adaptive in the short term, helping an organism respond to immediate stressors in ways that increase the chances of survival (e.g., diverting energy away from unnecessary functions such as maintenance of immune strength to activities that will help with immediate survival such as increased blood flow and muscle activity; Sapolsky et al. 2000). Such a diversion, although beneficial in the short term, can be costly when prolonged. Indeed, chronically elevated corticosterone can negatively impact survival, reproduction, growth, and immune function (e.g., Belden et al. 2005; Martin et al. 2005; Pride 2005; Ouyang et al. 2011).

3 Does Noise Cause Physiological Stress in Wildlife?

Research on traffic noise as a stressor in nonhuman animals has received relatively little attention beyond laboratory studies on rats, the findings of which are potentially limited in the degree to which they may be extrapolated to wildlife. Of the existing work on nonrodents, the majority focuses on birds and fish (e.g., Smith et al. 2004; Anderson et al. 2011; Hayward et al. 2011; Blickley et al. 2012). We are aware of no study that has determined whether noise is a physiological stressor in amphibians.

We recently conducted an acoustic playback experiment with field-caught female wood frogs (*Lithobates sylvaticus*) to determine whether traffic noise causes physiological stress. The ability to detect male breeding displays is critical in this species for which mating occurs exclusively during a brief 5–10-day window immediately after the spring thaw. During this window, the males emerge from their over-wintering retreats, migrate to ephemeral ponds to breed, and begin chorusing; the females arrive soon after (Wells 1977; Berven 1981). Consequently, acoustic interference with mating activity may be an environmental stressor. Using a stratified random design, we exposed 38 female wood frogs to one of three treatments: synthetic traffic noise plus a male wood frog chorus (13), chorus alone (12), or silence (13) for ~12 h overnight. After the treatments, we obtained blood samples and quantified plasma corticosterone. The females exposed to noise plus chorus had concentrations of corticosterone that were two to five times greater than those exposed to the controls.

4 Future Research Directions

Future work should focus specifically on amphibians and reptiles, which are vastly underrepresented in studies on the impact of anthropogenic noise on glucocorticoid production. Additionally, we need to identify the consequences of noise-induced chronically elevated glucocorticoid levels. For example, research should seek to determine how organisms with chronically elevated levels of glucocorticoids fare in the long term. Findings from studies on other environmental stressors suggest that prolonged, elevated glucocorticoid levels have fitness consequences (e.g., Romero and Wikelski 2001; Pride 2005). Determining the subsequent physiological and behavioral outcomes of increased glucocorticoid production will contribute substantially to our understanding of population-level consequences of anthropogenic noise. Furthermore, research aimed at identifying the components of anthropogenic noise that are the sources of physiological stress will make substantial gains in noise mitigation and conservation efforts. Finally, further studies exploring species' abilities to acclimate or adapt to novel acoustic environments would be of much interest in the field.

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Chapter 143
Harp Seals Do Not Increase Their Call Frequencies When It Gets Noisier

John M. Terhune and Thijs Bosker

Abstract Some species avoid low-frequency masking by shifting their calls to higher frequencies. We addressed the hypothesis that *Pagophilus groenlandicus* (harp seals) will make more high-frequency underwater calls to avoid low-frequency conspecific masking as calling rates increase. The spectral shapes at high and low calling rates were compared (after equalizing the broadband amplitudes). There were no significant differences between the spectral shapes. *Pagophilus groenlandicus* do not alter the proportions of low- and high-frequency calls as it gets noisier. This suggests that they may not shift their calling frequencies when encountering low-frequency, broadband anthropogenic noise.

Keywords Pagophilus groenlandicus • Harp seal • Underwater vocalizations • Antimasking • Frequency shift

1 Introduction

Every spring, *Pagophilus groenlandicus* (harp seals) form large breeding herds on sea ice off the east coast of Newfoundland and Labrador (the Front herd) and in the Gulf of St. Lawrence (the Gulf herd). The seals have a large underwater vocal repertoire of over 18 call types (Terhune 1994). Calling rates often exceed 100 calls/min, and at high calling rates, the calls themselves can produce a virtually continuous background noise (Terhune and Ronald 1986). The sea ice at the Gulf is relatively thin and in low wind conditions generates little underwater noise. The ice at the Front has typically thicker floes and ice noises are usually a more prominent

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feature of the soundscape. In response to the noisy environment, the underwater calling patterns of *Pagophilus groenlandicus* have evolved antimasking attributes such as a large repertoire of short-duration calls often repeated in a regular rhythm, with temporal separation at low calling rates and frequency separation of calls that are overlapped (Serrano and Terhune 2002; Moors and Terhune 2003).

Some species (e.g., great tits [*Parus major*], Slabbekoorn and den Boer-Visser 2006; right whales [*Eubalaena* sp.], Parks and Clark 2007) appear to be able to reduce masking by shifting the frequency (pitch) of their calls upward in the presence of low-frequency noise. This shift in pitch could prove effective for *Pagophilus groenlandicus* as well because with increasing calling rates, conspecific masking will occur more frequently. By utilizing calls that have a higher pitch, the *Pagophilus groenlandicus* could reduce the low-frequency masking effect. We addressed the hypothesis that *Pagophilus groenlandicus* will utilize higher frequency calls in response to conspecific masking as calling rates increase. To test this, we compared the overall spectral shape of their underwater calls at higher and lower calling rates within each of the two herds.

2 Methods

Underwater recordings were made on an opportunistic basis in the Front herd in 2003 and the Gulf herd in 2004. We obtained 5 recordings in the Front herd and 11 in the Gulf herd. Recordings were made during daylight when weather conditions permitted helicopter flights. A Vemco VLHT hydrophone was deployed at a depth of 10 m and attached to a Sony TCD-D100 digital tape recorder using 60-, 90-, or 120-min cassettes. A calibration tone was recorded at the beginning of each recording. Calling rates were determined by counting the numbers of calls for each of ten random samples of 15 s (Gulf) or 30 s (Front; due to lower calling rates, a longer sampling time was used) per recording. Counts were made by listening to the playback while visually monitoring a real-time spectral analysis (Gram, version 6.0.9).

Within each herd, tapes with the two lowest and two highest calling rates (the extremes per herd) were analyzed. A long-term average spectral analysis was performed on 100 random 1-s samples per recording using Multi-Speech (model 3,700, version 2.29). The analysis bandwidth was 43.1 Hz over the range of 0–20 kHz. Sound levels were determined at 1/3-octave intervals (or nearest 43.1-Hz band) from 0.08 to 20 kHz. For each herd, the averaged mean spectral values of the two lowest and two highest calling rates were determined, resulting in four different groups (Front-Low, Front-High, Gulf-Low, and Gulf-High). A paired *t*-test indicated that there were no significant differences between the mean spectral levels of the Gulf-High calling rate and the Front-Low calling rate (see Results). To compare the spectral shapes of all four spectra, the broadband levels within each herd were adjusted to the same amplitude by adding 9.7 dB to the Front-High spectra and subtracting 3.2 dB from the Gulf-Low spectra. The amplitude adjustment resulted in the broadband levels of the four spectra being equal. This permitted a direct comparison of the spectral shapes. That is, if one of the spectra had a higher proportion of high-frequency components than the others, the means levels at 1/3-octave intervals should show a significant difference. The four spectra were compared using paired *t*-tests and Spearman *r* correlations.

3 Results

The Front recordings included noticeable ice noises, including squeaks when floes rubbed together that interfered with determining the call rate. The Gulf recordings were characterized by *Pagophilus groenlandicus* calls with little ice noise. The calling rates (calls/min) of the tapes selected for analysis ranged between 43.0 and 56.0 (mean 49.5; Front-Low), 73.8 and 77.8 (mean 75.8; Front-High), 93.6 and 102.4 (mean 98.0; Gulf-Low), and 128.8 and 131.2 (mean 130.0; Gulf-High). For both the Front and Gulf herds, sound levels of each 1/3-octave interval were higher for the lower calling rates than for the higher calling rates.

A paired *t*-test of the levels of the 24 measures at 1/3-octave intervals found no differences between the Front-Low and Gulf-High values ($t = 0.21$; $df = 23$; $P = 0.84$), whereas all other pairings were significantly different ($t > 4.5$; $df = 23$; $P < 0.001$). After the amplitudes of the broadband levels of the other two samples were adjusted to be the same as either the Front-Low or Gulf-High, there were no significant differences between any of the four spectra ($t \leq 0.21$; $df = 23$; $P \geq 0.84$; Fig. 143.1).

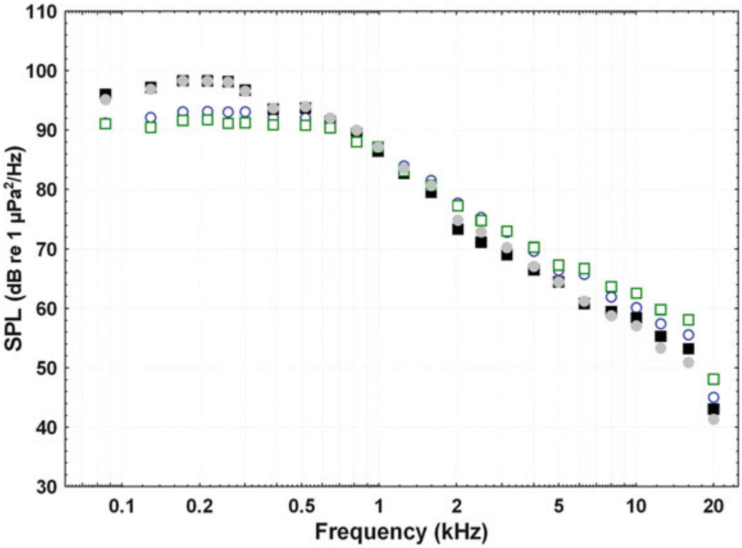

Fig. 143.1 Average sound pressure levels (SPL; spectrum level) at 1/3-octave intervals of *Pagophilus groenlandicus* underwater calls and ambient noise recorded in the "Front" breeding herd east of Newfoundland and the "Gulf" herd in the Gulf of St. Lawrence, Canada. *blue open circle*, Low calling rate, Front herd; *green open square*, high calling rate, Front herd adjusted to the same broadband level as the low calling rate; *black filled square*, high calling rate, Gulf herd; *gray filled circle*, low calling rate, Gulf herd adjusted to the same broadband level as the high calling rate. The amplitude adjustments were used to superimpose the four spectra so that the shapes could be directly compared; see text for details

The values of each of the four spectral groups were highly correlated ($r^2 \geq 0.98$; $t \geq 34.4$; $P < 0.0001$; $n = 24$). There were minor differences between the spectra of the two herds. In the Gulf herd, levels below 0.4 kHz were proportionally higher than those in the Front herd. This likely reflects the higher proportion of seal calls contributing to the overall noise level. The Front values above 1.6 kHz were slightly higher than those from the Gulf. This reflects the higher presence of ice noise, especially the squeaks associated with ice floes rubbing together. The spectral shapes of the two herds were essentially identical between 0.4 and 1.6 kHz (Fig. 143.1).

4 Discussion

Overall, there were no shifts in the frequency bands utilized by the *Pagophilus groenlandicus* as the calling rates or ice noises increased. *Pagophilus groenlandicus* have a wide repertoire of calls, many of which have high amplitudes. The mean frequencies of the highest amplitudes of 6 of the 17 call types measured by Rossong and Terhune (2009) were above 1.6 kHz. Eleven of the seventeen call types had mean frequencies that were between 0.4 and 1.6 kHz, the region of the four spectra that overlapped completely. This indicates that *Pagophilus groenlandicus* did not switch to using calls that are higher pitched, even though they have the ability to produce these calls. Presumably, if the seals produced a higher proportion of these higher frequency calls, they could reduce the masking effect by lower frequency background noise.

Although *Pagophilus groenlandicus* did not seem to switch to higher pitched calls, it is important to realize that the behavioral functions of the various call types are unknown. All six of the higher frequency call types have a sinusoidal structure and thus differed from many of the other call types that are broadband and pulsed (Rossong and Terhune 2009). If the behavioral functions of these two broad classes of call types are different, then the seals may not have the opportunity to alter the proportional usage of these higher pitched call types.

In both herds, the overall amplitudes of the lower calling rates were higher than those of the higher calling rates. This is counterintuitive and the reasons why this occurred are unexplained. The ~10-dB differences in the Front herd are substantial and are not reflected by changes in the spectral compositions of the lower versus higher calling rates.

An additional finding from this study was related to determining the calling rate, which was more difficult than anticipated. It is likely that many of the calls in the Front herd were masked by ice noise; whereas in the Gulf herd, conspecific calls masked others that had a lower amplitude. Earlier studies that determined *Pagophilus groenlandicus* calling rates (e.g., Terhune and Ronald 1986) used recordings from portable reel-to-reel recorders that had a dynamic range of less than −40 dB. In these recordings, it is likely that the noise limit of the recorder precluded detecting the quieter calls. In the current study, the digital audiorecorder dynamic range of approximately −80 dB meant that quieter, more distant seal calls could be detected.

When calling rates were high, any quieter calls would be masked by higher amplitude calls at similar frequencies. As calling rates dropped, the quieter calls could now be detected in the gaps between the higher amplitude calls, and as a result, the count of calls per minute remained high. For this reason, comparisons of calling rates obtained using recording systems with different dynamic ranges may not be appropriate.

Terhune and Ronald (1986, Figs. 1 and 5) reported a difference in the spectral shape of the Gulf *Pagophilus groenlandicus* spectra determined at one-octave intervals. The octave-band levels of the lowest calling rate (range 0–46 calls/min) were only a few decibels above the noise limits of the recording system and the averaging methods were less precise than those used in the current study. We were not able to obtain recordings from the Front or Gulf herd without seal calls with the Vemco-Sony DAT recording system so the relative spectral shapes of the Front or Gulf ambient noise are unknown. Our data do not address the spectral composition of the *Pagophilus groenlandicus* herds at very low calling rates.

To conclude, *Pagophilus groenlandicus* underwater vocal communication evolved under noisy conditions. The call structures, durations, repetition patterns, and calling behaviors contain antimasking attributes (Serrano and Terhune 2002). This study indicates that these attributes do not appear to include using more higher frequency calls as low-frequency noise increases. It is doubtful that *Pagophilus groenlandicus* will be able to reduce the communication masking effects of continuous broadband low-frequency noises associated with anthropogenic noises.

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Chapter 144
Measuring In-Air and Underwater Hearing in Seabirds

Sara C. Crowell

Abstract Electrophysiological methods were used to measure the in-air hearing of 10 species of seabirds. There are currently no measures of the underwater hearing abilities of diving birds. In preparation for constructing a behavioral audiogram both in-air and underwater hearing, several species of diving ducks were raised. Because there is a considerable amount of literature on bird hearing in air, the technical setup and training methods were modeled on similar studies, with modifications to address the nature of the underwater sound field and the difficulty of the task for the birds.

Keywords Diving ducks • Sea ducks • Psychoacoustics • Auditory brainstem response

1 Introduction

The introduction of anthropogenic noise into an aquatic environment has the potential to affect animals in various ways, including masking communication, displacement from important breeding or foraging areas, disruption of predator-prey interactions, and causing physiological damage ranging from noise-induced threshold shifts to tissue damage.

Currently, all studies investigating the impacts of noise on aquatic animals have focused on marine mammals, fish, and some invertebrate species. Seabirds have been neglected in this realm, even though many species spend the majority of their lives away from land and a great portion of their lives underwater. Seabirds have the potential to be adversely affected by noise both in the air and underwater in ways similar to marine mammals and fish.

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2 Why Study Diving Birds?

There is little information available concerning seabird hearing, either in the air or underwater. Therefore, it is important to obtain accurate hearing thresholds for these species before the effects of noise on them can begin to be explored. In addition, there are several reasons why seabirds should be studied.

2.1 Comparison with Existing Avian Auditory Literature

Birds provide a useful model because in-air audiograms are already available for over 50 species, and the avian auditory system (as it works in air) is well investigated. Both the electrophysiological and psychoacoustic methods described here have been commonly used in the laboratory to examine the avian auditory system in many species. Birds on average hear best between 2 and 5 kHz, with absolute thresholds approaching 0-dB sound pressure level (SPL) in air. The average avian audiogram shows a loss of sensitivity below 1 kHz of ~20 dB/octave and a loss of sensitivity at high frequencies above 4 kHz of ~60 dB/octave (Dooling et al. 2000).

Major differences between the mammalian ear and avian ear include the number of middle ear bones (a single columella in the avian ear) and the shape of the sensory epithelium (an uncoiled basilar papilla in the avian ear). The inner ears of archosaurs (birds and crocodiles) show a high degree of structural similarity, a strong correlation with body mass, and a strong correlation between the length of the auditory sensory epithelium and the behavioral characteristics of hearing such as frequency and the high-frequency limit of hearing (Gleich et al. 2005).

2.2 Sound Is Important to Seabirds in Air

Although it is unknown if seabirds use sound underwater for communication or navigation, several studies have indicated that vocalizations are important to seabirds in air. Most penguin species rely on sound to individually identify their mates and chicks, to attract potential mates, and to defend territories. Emperor and King penguins have evolved complex vocalizations for individual recognition among several thousands of unrelated birds in the tightly packed, noisy colony (Aubin et al. 2000). In fact, Emperor penguins cannot identify their mates or chicks visually (Jouventin 1982) and instead rely solely on individually distinctive, amplitude-modulated vocalizations. Little blue penguins (*Eudyptula minor*), a nocturnal, cave-dwelling species, can distinguish individuals through the use of auditory cues (Nakagawa et al. 2001).

2.3 Seabirds Are Amphibious Animals

Amphibious animals such as seabirds, pinnipeds, and anurans face the challenge of hearing in media with great acoustic impedance differences. These animals may use different mechanisms for hearing in each medium, and adaptations for diving may impact hearing abilities. For example, in pinnipeds, at shallow depths, the tympanic membrane is in contact with air on both sides, presenting an impedance mismatch that would tend to cause sound to travel through an alternate pathway through the head (like bone conduction; Kastelein et al. 1996). Some seabird species, like pinnipeds, have several adaptations to compensate for increasing pressure while diving. These may or may not affect their hearing abilities. In some penguin species, the meatal opening can be closed by surrounding muscles while diving, trapping air inside. The middle ear and meatus are also covered with a corpus cavernosum, a highly vascularized tissue that fills with blood to compensate for increasing pressure on the tympanic membrane as the animal dives (Repenning 1972; Sadé et al. 2008). If this tissue is flooded with blood on both sides of the tympanic membrane, it is possible that acoustic conductance could occur through the traditional tympanic route (Au and Hastings 2008). Christensen-Dalsgaard and Elepfant (1995) hypothesized that in anurans, air in the lungs vibrates much like air in a swim bladder in a fish and that these vibrations are coupled to the middle ear via the larynx. Resonance of the air-filled middle ear may also play a role in underwater hearing in turtles (Willis et al. 2013).

2.4 Any Information on These Species Is Valuable

Many seabird species spend little time near the coastline and only come to land for nesting. Because they generally occur in remote offshore habitats, they are difficult to study and basic information on population size, migratory patterns, foraging habits, and physiology is lacking. In addition, many duck species are valued by hunters so there is considerable interest in any information that could assist with their management. Knowledge of the auditory capabilities of these species would therefore be valuable in adding to the available information, especially pertaining to management issues concerning the introduction of noise into flyways or critical stopover points.

3 Specific Birds Included in This Investigation

Currently, hearing tests have been conducted on 10 species of seabirds and 1 species of crane. The majority of the species tested are sea ducks and diving ducks. Although sea ducks do dive, they can be distinguished from diving ducks by their inclusion in a separate subfamily within Anatidae (ducks, swans, and geese) that are essentially marine outside the breeding season. Here are a few of the species of seabirds tested.

Lesser scaup (*Aythya affinis*) are medium-size diving ducks that feed primarily on mollusks, crustaceans, and aquatic insects. They are capable of diving to depths of at least 15–18 m for 2–25 s at a time. Both males and females vocalize throughout the year to signal to mates and offspring. The lesser scaup is one of the most abundant and widespread species of diving duck, but its numbers have been declining in recent years for reasons unknown (Austin et al. 1998).

Long-tailed ducks (*Clangula hyemalis*) are the deepest divers of all diving and sea ducks, reaching at least 60 m in depth to search for crustaceans, fish, and mollusks. Also, they are arguably the most vocal of the sea ducks, with their distinctive and often incessant ow-owoolee male call. They are a true Arctic species, breeding in tundra and taiga regions (Robertson and Savard 2002).

Red-throated loons (*Gavia stellata*) are the smallest members of the loon family. They pursue live fish underwater, including herring, capelin, and sculpin. They do not “yodel” like other loon species but instead use their “plesiosaur call” as a territorial duet (Barr et al. 2000).

Northern gannets (*Morus bassanus*) are the largest indigenous seabirds in the North Atlantic. They obtain live fish, mostly mackerel and herring, through plunge diving, during which the bird starts from a height of 10–40 m above the water and plunges into the water with speeds >100 km/h. They then pursue fish up to 15 m deep in the water by swimming. They breed in dense, noisy colonies on cliffs or islands (Mowbray 2002).

4 Electrophysiological Versus Behavioral Methods

Both behavioral and electrophysiological methods were used to test hearing in seabirds. The auditory brainstem response (ABR) is a valuable physiological technique used to test a bird’s hearing in a minimally invasive and time-efficient manner (Brittan-Powell et al. 2002). The ABR is a scalp-recorded potential resulting from a synchronized neural discharge (population response), manifested as a series of four or more waves occurring within the first 10 ms after stimulation. The ABR has been used as a tool for studying the functionality of the auditory system in a wide variety of animals, including several species of birds (e.g., Dmitrieva and Gottlieb 1992; Brittan-Powell et al. 2002, 2005).

Although the ABR is useful for obtaining a fast estimate of hearing thresholds, many studies have demonstrated that behavioral psychoacoustic measures provide more sensitive threshold measurements (Fay, 1988), so two species of ducks were also trained to behaviorally respond to sound for in-air and underwater hearing tests. These birds were raised from eggs in captivity and were tested in large concrete diving tanks at the US Geological Survey Patuxent Wildlife Research Center’s captive seabird facility.

5 Results

The typical ABR waveform for all species tested showed 2–3 prominent peaks that occurred within the first 5 ms after onset of the stimulus. Peak amplitude increased and peak latency decreased with increasing stimulus sound pressure level. Hearing sensitivity peaked between 1,500 and 3,000 Hz. Both the waveform morphology and response characteristics of the peaks to changing stimulus intensity are similar to those found in other avian species such as screech owls (*Megascops asio*) and budgerigars (*Melopsittacus undulatus*).

The audiogram obtained from in-air psychoacoustics with lesser scaup was similar to that obtained with ABR in its U-shape as well as in the region of greatest sensitivity but differed in absolute thresholds that were up to 30 dB more sensitive (Therrien et al., in preparation). Underwater psychoacoustic experiments are ongoing, with several challenges that had to be considered, including nonideal sound fields in an underwater tank environment and working with animals that are positively buoyant in water and cannot stay under as long as marine mammals or fish. Careful mapping of the acoustic field in the tank was used to inform the placement of the speaker and observation target for the bird in a location where impacts from the water surface and tank walls are minimal. Adjustments in behavioral training were made to compensate for a more difficult task for the birds, including leaving the response target at the surface so that the birds hear the sound underwater but can surface to respond to it.

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Chapter 145
WODA Technical Guidance on Underwater Sound from Dredging

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Abstract The World Organization of Dredging Associations (WODA) has identified underwater sound as an environmental issue that needs further consideration. A WODA Expert Group on Underwater Sound (WEGUS) prepared a guidance paper in 2013 on dredging sound, including a summary of potential impacts on aquatic biota and advice on underwater sound monitoring procedures. The paper follows a risk-based approach and provides guidance for standardization of acoustic terminology and methods for data collection and analysis. Furthermore, the literature on dredging-related sounds and the effects of dredging sounds on marine life is surveyed and guidance on the management of dredging-related sound risks is provided.

Keywords World organization of dredging associations (WODA) • Dredging • Noise • Marine mammals • Fish

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1 Introduction

Covered by a number of regulatory frameworks and processes, including the EU Marine Strategy Framework Directive, underwater sound has also been identified by the Central Dredging Association (CEDA) as an issue that needs further consideration. Thus, in 2011, a CEDA Working Group on Underwater Sound (WGUS) was founded and published a position paper on underwater sound in relation to dredging (CEDA 2011). The paper received a great deal of attention from both within and outside CEDA. Based on the previous achievement, a World Organization of Dredging Associations (WODA) Expert Group on Underwater Sound (WEGUS) was established. The task of the WEGUS was to extend the previous achievements to a broader international audience and to provide a guidance paper on dredging sound, a review of impacts on aquatic biota, and advice on underwater sound-monitoring procedures (WODA 2013). Some key results from the paper are summarized here.

2 A Risk-Based Approach to Sound in Relation to Dredging

WODA recommends following a risk-based process in assessing sound-related impacts from dredging (see, for example, Boyd et al. 2008; Fig. 145.1). This will result in a more systematic approach to acoustic impact studies. With regard to risk

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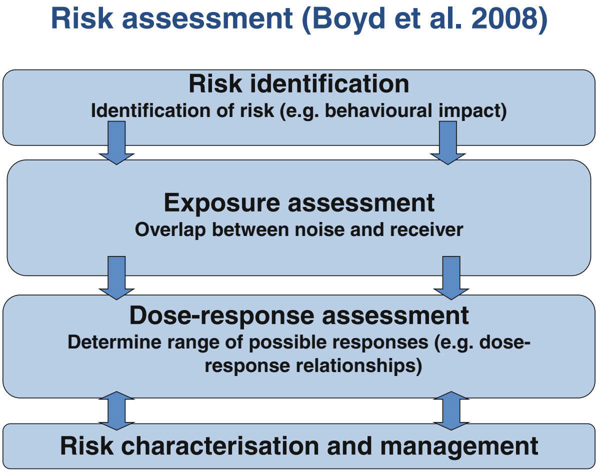

Fig. 145.1 Overview of the risk-based approach to investigate sound-related risks

identification, it is advised to use an appropriate framework whereby risks can be divided into the categories of masking, response, temporary (TTS) or permanent (PTS) threshold shift, and injury (see Richardson et al. 1995). However, it is important to recognize that these impact zones are partially overlapping and are not simply related to distance between the source and the exposed organisms. Consideration must be given to the fact that the physiological effects are related to the dose of exposure, which also involves the duration of the impact (Southall et al. 2007). Physiological effects could potentially occur at sound pressure levels (SPLs) that do not cause a behavioral response if the exposure duration is sufficiently long.

For the exposure assessment, standardization of acoustic terminology is a prerequisite (see WODA 2013). It is easy to misuse the many different notations of underwater sound and make comparisons based on inconsistent decibel values. Great care must be taken in any reference to inferred SPLs based on the source strength and the distance between the source and the observation location. The underwater sound distribution should be described using underwater acoustic models supported by empirical field data to the fullest extent practical.

With regard to the characterization of dredging sounds, progress is being made and a lot more is known now than some years ago. Dredging sounds can be associated with sediment excavation, propulsion of dredging vessels during transport, and dredged material placement. A given project may involve one or more of four basic types of dredgers: cutter suction dredger, trailing suction hopper dredger, grab dredger, and backhoe dredger. Sound sources associated with different types of hydraulic and mechanical dredge processes can be very manifold (Fig. 145.2). Very detailed measurements on a number of trailing suction hopper dredgers have been performed. Information on grab and backhoe dredgers has become available as well. Existing data indicate that source levels associated with most dredging processes are generally comparable with those of merchant ships, with the exception of

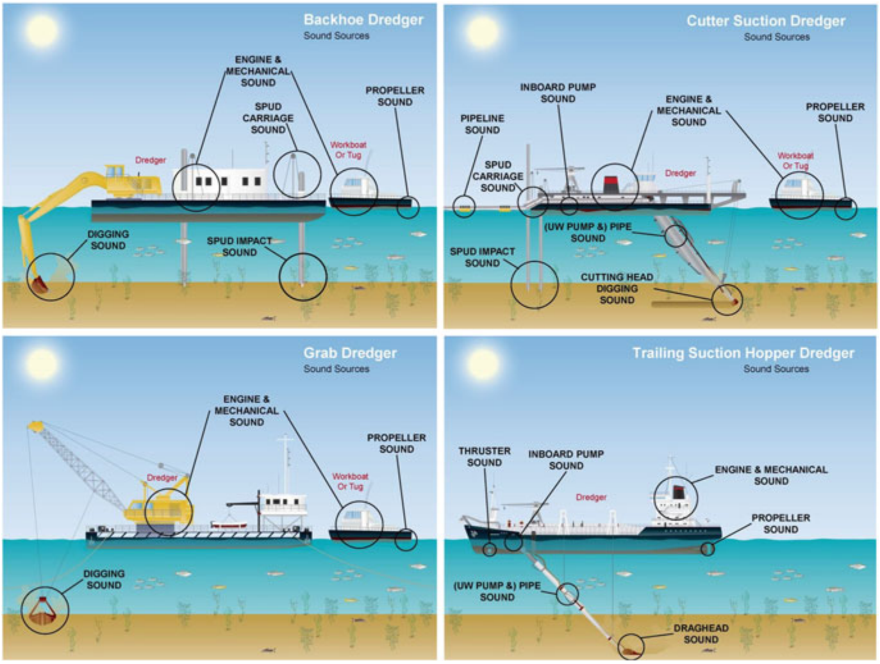

Fig. 145.2 Sound sources for main dredger types

elevated levels of noise generated by gravel extraction (de Jong et al. 2010; Robinson et al. 2011; Reine et al. 2012a, b). Despite an increased knowledge of dredging sounds, we do not yet have a complete understanding of acoustic emissions from dredging because not all sources that are shown in Fig. 145.2 are covered and measurements are still not fully standardized. Looking at the receptor organisms, it is necessary to define the population that will be subject to the sound exposure. This, however, is very challenging due to variability in population estimates (Thomsen et al. 2011).

One remaining key challenge is the dose-response assessment, i.e., the assessment of the relationship between the properties of the received sound and the effects that it has on marine life. Metrics other than overall dose in terms of the cumulative sound exposure level (SEL) may also be relevant for the physiological effects (e.g., peak sound pressure, rise time, kurtosis), but data confirming such effects are lacking. Behavioral effects are usually related to the SPL for a stated averaging time (either the duration of the transient signal or a "long-term" average for ambient sound). Results from studies investigating the effects of sound on marine mammals, fish, and other aquatic life are, to date, highly equivocal. Some cetaceans have been observed avoiding areas of dredging activity on a temporal basis (reviewed by Richardson et al. 1995 and a recent study by Diederichs et al. 2010). No peer-reviewed information exists about the effects of dredging-induced sound on seals or fish.

Due to the above uncertainties, risk characterization and the management of risks related to the dredging sound are challenging. It is clear that the dredging sound has the potential to impact aquatic life, and it is assumed that most of these impacts would concern disruption of communication due to masking or alteration of behavior patterns. Cumulative and long-term exposures leading to TTS have to be considered, at least for marine mammals (Kastelein et al. 2012), although PTS or other auditory injuries are unlikely. If the assessment concludes that there is a high risk of an adverse effect, the risk management could involve mitigation measures. OSPAR (2009) identified several options including technical and operational ones. One very effective sound-mitigation measure might simply be adequate maintenance of the dredge plant, including lubrication and repair of winches, generators, propulsion components, and other potential sources, because well-maintained dredgers are much less likely to be "loud" dredgers. The WODA advice is to identify, assess, and manage the risk following the framework outlined above. In conclusion, assessments of dredging sound-induced impacts may require different approaches depending on the organisms and effects of concern and the type and location of the project.

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Chapter 146
Noise Exposure Criteria for Harbor Porpoises

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Abstract Despite a major research effort, no generally accepted exposure limits are available for harbor porpoises. Recent studies of the temporary threshold shift (TTS) in porpoises indicate that the sound exposure levels (SELs) required to induce low levels of TTS depend on stimulus frequency and roughly parallel the shape of the audiogram. A number of studies on behavioral avoidance reactions (negative phonotaxis) to pingers, seal scarers, and pile driving show a similar dependence on stimulus frequency. Both TTS and behavioral data suggest that weighting sound pressure levels with a filter function resembling the inverted audiogram would be appropriate.

Keywords *Phocoena phocoena* • Temporary threshold shift • Behavioral response • Pile driving • Pinger • Seal scarer

1 Introduction

One of the most common cetaceans in coastal and shelf waters in the northern hemisphere, some of the noisiest waterways in the world, is *Phocoena phocoena* (harbor porpoise). Unfortunately, *P. phocoena* is generally believed to be one of the most sensitive species of marine mammals with regard to acoustic disturbance, which makes it a key species in discussions of the impact of increasing anthropogenic noise in the oceans. Despite this, there are no commonly accepted limits for regulating noise impacts on this species. Southall et al. (2007), in their much cited work on noise criteria limits, extended the exposure limits they developed for midfrequency (MF) cetaceans (dolphins, beaked whales) to cover also high-frequency (HF)

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cetaceans (including porpoises). However, they did so by clearly stressing the need for additional experimental data and hinted that the HF cetaceans were likely to be more sensitive than the MF cetaceans.

Noise can affect marine organisms in several ways. Most attention to date has been on the three types of impact listed by Richardson et al. (1995): direct injury, behavior effects, and, to a lesser extent, the masking of hearing. Direct injury has received by far the greatest attention and this has resulted in a large body of experimental evidence. This evidence was used by Southall et al. (2007) to suggest exposure limits for MF cetaceans and pinnipeds as well as to extrapolate these limits to also cover low-frequency (LF) cetaceans and HF cetaceans. In contrast, experimental work on behavioral responses is scarcer and much less consistent. Accordingly, Southall et al. (2007) were unable to establish usable criteria for the onset of behavioral reactions. Southall et al. (2007) did not even attempt to consider masking because the experimental evidence is even scarcer still.

Since 2007, several new studies have produced new information on the susceptibility of *P. phocoena* (and closely related species) to injury and behavioral disturbance, calling for a review of this new information in an effort to provide the first suggestions for exposure criteria for this species.

2 Injury

The approach of Southall et al. (2007) in establishing safe exposure limits with respect to injury was based on the thresholds for inducing temporary threshold shifts (TTSs). Such thresholds were established experimentally, and the available results were extrapolated upward by Southall et al. (2007) to determine (precautionary) thresholds for eliciting permanent threshold shifts (PTSs). These were, in turn, used as the basis for exposure limits, with the argument that PTS is a conservative proxy for injury at large. Whether such exposure limits should be based on TTS or PTS is a separate discussion. What can be said is that although TTS is indisputably an injury (see, e.g., Kujawa and Liberman 2009), it is unclear what the long-term consequences are, in terms of fitness, for an animal experiencing low levels of TTS.

Despite this, TTS is a useful criterion for establishing exposure limits because it can be measured reliably in animals in captivity and it very likely constitutes the smallest possible direct damage noise can inflict on an animal when one ignores the putative physiological effects of intense infrasound.

2.1 Studies of TTS in Porpoises

Three studies are now available on TTS in *P. phocoena* and one on the closely related species *Neophocoena asiaorientalis* (Yangtze finless porpoise). Lucke et al. (2009) measured TTS induced in a single animal by exposure to short, broadband transient noise (air gun pulse) and found that 6 dB of TTS could be induced by a single pulse with a received sound exposure level (SEL) of 164 dB re 1 µPa^2·s. Peak frequency of the pulse was below 500 Hz, but substantial energy was present at higher frequencies up to and possibly above 20 kHz.

Kastelein et al. (2012) exposed a different animal to longer playbacks (between 7.5 min and 4 h) of octave-band noise centered at 4 kHz. Three sound pressure levels were used, that were in line with previous observations in *Tursiops truncatus* (bottlenose dolphins; Mooney et al. 2009), TTS could be induced at all three levels but required different exposure durations, indicating a trade-off between intensity and duration. Six decibels of TTS could be induced by a SEL of 163 dB re 1 µPa^2·s for the low-intensity noise and 172 dB re 1 µPa^2·s for the medium-intensity noise. In a subsequent study, Kastelein et al. (2013) induced 14 dB of TTS by exposure to a 1.5-kHz tone for 1 h, for a total SEL of 190 dB re µPa^2·s.

Popov et al. (2011) could induce 25 dB of TTS in *N. asiaorientalis* by exposing the animal to an SEL of 163 dB re 1 µPa^2·s for octave-band noise centered at 45 kHz. Taken together, the four studies indicate that the SEL required to elicit TTS depends on stimulus frequency, in a way roughly paralleling the shape of the audiogram.

3 Behavioral Disturbance

Animals can and will react to sound in many different ways, ranging from orientation (investigative) behavior to panic. Response duration can also vary from a brief startle response to persistent evasion for hours or even days. Ranking the different behaviors in terms of the severity of the impact on the long-time survival and reproduction of the animals (their fitness) is extremely difficult. Still difficult but more manageable is a ranking based on the immediate reactions of the animals, ranging from orientation response to panic. Such a scaling was developed by Southall et al. (2007) and included nine classes of response of increasing severity. However, applying a response severity scale to behavioral reactions to high-intensity sounds in practice is very difficult, primarily because the reactions often occur at very large distances from the sound source and hence are difficult to observe. To simplify the analysis, we have dismissed scaling of the responses and considered the onset of negative phonotaxis (i.e., avoidance) as a suitable basis for a criterion to define a significant behavioral reaction to noise. This corresponds to severity scale scores of 6–9 on the scale of Southall et al. (2007). Sustained negative phonotaxis manifests itself in a decreased abundance of animals in a smaller or larger area around the sound source and the impact of the sound can be quantified by the deterrence distance.

Such a displacement of animals may constitute a temporary loss of habitat with potential energetic consequences (e.g., Williams et al. 2006) and, depending on circumstances, potentially also affect the long-term population size in the area. With an appropriate study design, it is also easier to detect than many other responses.

An extensive series of laboratory measurements of porpoise behavioral responses for a wide variety of sounds is available (e.g., Kastelein et al. 1995, 2001, 2008).

However, extrapolation of response thresholds from experiments in captivity to the field is difficult for various reasons (see discussion in Wright et al. 2009). Thus, given the relatively large number of field experiments, we have focused on the latter and omitted results from captive animals.

3.1 Reactions to Pingers

A number of studies have focused on the reactions of porpoises to acoustic deterrent devices (pingers), two of which have sufficient information to derive estimates of reaction thresholds. Both studies involved visually tracking porpoises around inactive versus active pingers.

Culik et al. (2001) observed an avoidance reaction at a distance of at least 200 m in response to a PICE pinger (FM sweeping 20–160 kHz), corresponding to a reaction threshold of 93 dB re 1 μPa root-mean-square (rms). In the same fashion, Carlström et al. (2009) found reaction distances to a Dukane Netmark 1,000 pinger (11 kHz) in the range of 125–375 m equal to an estimated received level of 78 dB re 1 μPa rms.

3.2 Reactions to Seal Scarers

Four studies are available on the reactions to acoustic harassment devices (seal scarers), three of which are based on theodolite trackings from land while the last (Brandt et al. 2012) is based on passive acoustic monitoring and aerial surveys.

Olesiuk et al. (2002) studied the reactions to a seal scarer (Airmar AHD; 10 kHz), reporting a dramatic decline in porpoise observations out to the maximum sighting distance of 3.5 km when the seal scarer was on. This equates to a maximum estimate of the sound pressure level at a threshold of ~110 dB re 1 μPa rms, calculated for individual 1.8-ms pulses. If the temporal integration of the porpoise auditory system is considered (estimated at 125 ms), the sound pressure level of a long-duration pure tone with the same detection threshold would be 97 dB re 1 μPa rms, which is the appropriate number to use in comparison with other studies. In a very similar study (Johnston 2002) with a comparable seal scarer (Airmar dB II Plus; 10 kHz), reactions out to at least 1 km were noted, corresponding to an estimated sound pressure level equivalent to 107 dB re 1 μPa rms for a 1-s pure tone.

The two most recent studies (Brandt et al. 2012, 2013) used a different type of seal scarer (Lofitech; 14 kHz). Brandt et al. (2012) used passive acoustic monitoring (C-PODs) around the seal scarer and detected significant reductions in porpoise acoustic activity out to distances of 7.5 km, corresponding to a received sound pressure level of 98 dB re 1 μPa rms. The other study (Brandt et al. 2013) used the same seal scarer but relied on theodolite observations made from a cliff. In this experiment, reactions were seen down to received levels of ~120 dB re 1 μPa rms.

3.3 Reactions to Pile Driving

A number of studies have looked at the reactions of porpoises to pile-driving operations in connection with their construction. All have been conducted by means of passive acoustic monitoring at various distances from the pile-driving site. Tougaard et al. (2009) studied reactions to pile driving at the Horns Reef 1 offshore wind farm. Reactions were seen at distances beyond 21 km from the construction site, equating to an estimated received level of 130 dB re 1 μPa rms.

At the Horns Reef 2 offshore wind farm, Brandt et al. (2011) observed reactions out to a distance of 18 km but not at 21 km. Noise levels at 18 km were extrapolated out to a received single-pulse sound exposure level of 149 dB re 1 μPa rms. A third study at the Alpha Ventus offshore wind farm (Dähne et al. 2013) gave similar results, with reaction distances ~25 km. The associated aerial surveys support the conjecture that porpoises leave the impact area rather than diminishing vocal behavior. Noise measurements made 17 km from the construction site allowed extrapolation to received levels of ~140 dB re 1 μPa rms at 25 km (Betke and Matuchek 2011). Finally, Thompson et al. (2010) investigated reactions of porpoises to pile driving at a single station in the Beatrice offshore wind farm located 40 km from the piling station and could not detect changes in porpoise abundance. Sound pressure levels were estimated to be ~120 dB re 1 μPa rms.

3.4 Scaled-Down Controlled Exposure Experiments

To overcome the difficulties of studying the large impact area in a real pile driving, Tougaard et al. (2012) conducted a play-back experiment with pile-driving noise at reduced source levels, allowing animals to be tracked by theodolite at deterrence distances of ~200 m. This corresponded to a received sound pressure level of ~130 dB re 1 μPa rms.

The results of the 12 different field experiments are remarkably consistent. Reaction distances to real pile-driving events appear to be on the order of 20 km; reactions to seal scarers are 1 order of magnitude below, between 1 and 7.5 km; and reactions to pingers are still another order of magnitude lower, ~200 m. The three groups differ in several different ways: source level, the frequency band where most energy is located, and pulse duration and pulse repetition rate. Keeping this in mind, there is a clear pattern in the results, with the lowest thresholds for pinger signals, which have energy at high frequencies; medium thresholds for seal scarers, with medium frequency signals (10–14 kHz); and highest thresholds for pile-driving noise, where the peak energy is <1 kHz.

This suggests that a most important factor determining whether porpoises react or not is the sound pressure level above the hearing threshold, also referred to as the sensation level.

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Chapter 147
Review of Offshore Wind Farm Impact Monitoring and Mitigation with Regard to Marine Mammals

Ursula K. Verfuss, Carol E. Sparling, Charlie Arnot, Adrian Judd, and Michael Coyle

Abstract Monitoring and mitigation reports from 19 UK and 9 other European Union (EU) offshore wind farm (OWF) developments were reviewed, providing a synthesis of the evidence associated with the observed environmental impact on marine mammals. UK licensing conditions were largely concerned with mitigation measures reducing the risk of physical and auditory injury from pile driving. At the other EU sites, impact monitoring was conducted along with mitigation measures. Noise-mitigation measures were developed and tested in UK and German waters in German government-financed projects. We highlight some of the review's findings and lessons learned with regard to noise impact on marine mammals.

Keywords Offshore wind farm • Impact monitoring • Mitigation • Marine mammals • Licensing procedure

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1 Introduction

In the United Kingdom, postconsent monitoring requirements are incorporated into offshore wind farm (OWF) license conditions. The aims of this monitoring are to validate or reduce uncertainty in the predictions of environmental impacts, focusing on areas of key risk identified in the Environmental Impact Assessment process and to assess the effectiveness of mitigation measures. The Department for Environment, Food and Rural Affairs and the Marine Management Organisation commissioned a review of all postconsent monitoring data collected from UK OWF developments to date to provide a synthesis of the evidence associated with observed environmental impacts and make recommendations for maximizing the effectiveness of the licensing process and future monitoring. This review also covers OWFs built outside the United Kingdom in European Union (EU) waters to provide further insights into the monitoring and mitigation best practices and lessons learned about their impact on the marine environment. We highlight some of the review's findings in relation to the impact of underwater noise on marine mammals, using a comparative approach, incorporating an analysis of progress over time and a summary of lessons learned from the monitoring outcomes.

2 Studies Included

Environmental statements, licenses, and monitoring and mitigation reports were reviewed from a total of 19 consented UK OWFs. These sites and their generation year are listed in Table 147.1.

Publicly available reports and publications from nine operating OWFs in Belgium (Thornton Bank), Denmark (Horns Rev I + II, Nysted, Sprogø), Germany (Alpha Ventus, Borkum West II), and The Netherlands (Offshore Windpark Eegmond aan Zee [OWEZ], Prinses Amalia) were reviewed to investigate marine mammal monitoring and mitigation conducted outside the United Kingdom.

Table 147.1 Generation year and name of the UK offshore wind farm sites reviewed

Generation year	Offshore wind farm site
2003	North Hoyle
2004	Scroby Sands
2005	Kentish Flats
2006	Barrow
2007	Burbo Bank
2008	Lynn/Inner Dowsing
2009	Gunfleet Sands I + II, Rhyl Flats, Robin Rigg E + W
2010	Greater Gabbard, Thanet
2011	Ormondo, Sheringam Shoal, Walney 1 + 2
2012	London Array, Teeside
2013	Gwynt Y Mor, Lincs, West of Duddon

3 Outcome

3.1 Impact Monitoring: Methods and Lessons Learned

UK Sites

Only two impact monitoring studies with regard to marine mammals were prescribed as part of license conditions at UK OWFs. At Scroby Sands, aerial survey haul-out counts were conducted during the summer months before, during (although not directly coinciding with the period of pile driving), and after the construction phases to monitor a mixed haul of *Phoca vitulina* and *Halichoerus grypus* (harbor and gray seals, respectively) situated <2 km away from the OWF site (Skeate and Perrow 2008; Skeate et al. 2012). The data indicated a decline in harbor seal numbers during construction, with numbers remaining lower in the two subsequent years. The numbers of gray seals, however, increased year after year throughout the construction and early operational periods. It is therefore possible that changes in harbor seal numbers were in response to this rather than to any effects of the OWF. There were also regional changes in patterns of haul-out use by harbor seals in the Wash over the same period, so changes at Scroby Sands could have been part of wider regional dynamics.

At Robin Rigg, boat-based surveys for cetaceans were conducted before, during, and after construction (Walls et al. 2013). Density surface models created using sightings data suggested that *Phocoena phocoena* (harbor porpoise), the only frequently sighted cetacean, were displaced from the wind farm site during construction. However, with only 1 year of preconstruction survey, natural variation cannot be ruled out as the reason for the observed change. Furthermore, other parts of the survey area outside the wind farm site also appeared to experience significant declines in harbor porpoise density.

European Union Outside the United Kingdom

In Belgium, Denmark, Germany, and The Netherlands, impact studies focused on harbor porpoises, but studies were also carried out on harbor and gray seals. Most porpoise studies were conducted using a before-after control-impact (BACI) design, with data collection during a time period before (B) and after (A) the impact in a control (C) and the wind farm impact area (I). In Belgium, Denmark, and Germany, data were also collected during wind farm construction, allowing the determination of the pile-driving impact radius. For the OWF Prinses Amalia, only impact monitoring reports covering the second year of operation were available for review.

Static passive acoustic monitoring (PAM) was the most common methodology used to investigate potential changes in porpoise presence as a result of offshore wind-related impacts using cetacean detectors (T-PODs and C-PODs, Chelonia Ltd.) moored across a control and the predicted impact area. These devices are standalone, archival data loggers that detect and log sound, storing certain parameters of odontocete echolocation clicks. In Belgium, Denmark and Germany, aerial or boat-based line transect surveys have also been conducted. Seals were studied by tagging animals of nearby haul-out sites with satellite or global system for mobile communications (GSM)/GPS transmitters or by monitoring numbers at the haul-out site.

The primary generic conclusion with regard to the impact of OWFs on marine mammals is that construction activities, especially pile driving, can have a significant impact on marine mammal abundance and distribution (e.g., seals: Edrén et al. 2010; porpoises: Brandt et al. 2011). In contrast, the operation of wind turbines has no significant negative effect (e.g., porpoises: Scheidat et al. 2011; seals: McConnell et al. 2012). The effect of pile driving may extend to distances beyond 20 km from the noise source. Investigations at Borkum West II revealed that a median sound exposure level (SEL) of 144 dB re 1 $\mu\text{Pa}^2\cdot\text{s}$ and above evoked a disturbance reaction in porpoises (Pehlke et al. 2013). This result is consistent with experiments in a captive harbor porpoise that revealed a threshold level for aversive behavioral reactions above an SEL of 145 dB re 1 $\mu\text{Pa}^2\cdot\text{s}$ (Lucke et al. 2009). The impact-monitoring studies show that harbor porpoises return to the wind farm sites after hours or days once piling ceases, but it is not known if this applies to the animals being displaced or to "new" animals entering the area. In the latter case, the resulting impact may be more severe than in the former (Tougaard et al. 2006). There are limited data on the relationship between piling duration and length of displacement. It is important to note that behavioral changes are not necessarily caused by piling (alone). They can also be induced by other construction activities such as seismic surveys, increased ship traffic, or the deployment of pingers and seal scarers intended to move animals away from an area immediately around the piling to reduce the risk of physical and auditory injury.

3.2 Mitigation Measures

UK Sites

In the United Kingdom, the licensing conditions for marine mammals have been largely related to mitigation measures, required to reduce the risk of physical and auditory injury from pile driving. A clear progression in the mitigation requirements was noticeable in the licensing conditions through time (2003–2010), likely connected to an increasing awareness of the severity of the possible impact of construction noise on marine mammals. Although early licenses contained no requirements for marine mammal mitigation, later licenses detailed prescribed mitigation measures by requiring soft starts and/or a delay to the start of piling when marine mammals were sighted close to the construction site. Licenses dated from 2007 onward prescribed detailed mitigation measures, including soft starts, monitoring of an exclusion zone with dedicated marine mammal observers (MMOs) and PAM, and enhanced PAM during piling at times with low visibility (e.g., at nighttime, unfavorable weather conditions). The size of the mitigation monitoring zone was not detailed within the licenses, but when described in the marine mammal mitigation protocol or monitoring report (7 cases), its radius was 500 m. Although the use of acoustic deterrent devices (ADDs) such as pingers or seal scarers was not mandatory in any of the licenses, they were deployed at three sites to displace marine mammals from the construction site. Where the marine mammal mitigation measures were detailed (four reports), very few instances of detections were reported, with only one acoustic and one visual harbor porpoise detection, each at a different site, causing a delay in piling.

European Union Outside the United Kingdom

In Belgium and The Netherlands, seasonal restrictions for pile driving from January to April (Belgium) or May (The Netherlands) have been applied to protect sensitive periods for key species such as the harbor porpoise and seals. Germany and Belgium have prescribed threshold values for impulsive (pile-driving) noise: the Belgian indicator of the Marine Strategy Framework Directive Descriptor 11 for impulsive noise requires emitted impulsive sound to be below 185 dB re 1 μPa zero-to-peak sound pressure level (SPL) at 750 m from the source. Exceeding this level leads to the requirement for noise-mitigation measures (Degraer et al. 2012). In Germany, emitted impulsive sounds must not exceed threshold levels of 160 dB re 1 μPa^2·s (SEL) or of 190 dB re 1 μPa peak to peak (SPL) at 750 m from the piling site (UBA 2011). This threshold is based on a temporary threshold shift (TTS) found in a harbor porpoise at 164 dB re 1 mPa^2·s SEL and 199 dB re 1 μPa SPL (Lucke et al. 2009). Information on the extent to which these thresholds have been met during OWF construction is limited. There is also the requirement for acoustic deterrent devices and soft-start procedures to ensure the absence of marine mammals within close range before piling (Verfuss et al. 2012). To meet the prescribed thresholds, noise-mitigation techniques reducing the transmitted sound have been developed, applied, and evaluated (further discussed in Section 3.2.3). ADDs such as pingers and/or seal scarers have been used in most studies reviewed in conjunction with pile driving to deter harbor porpoises and seals out of the impact area. Gravity-based (and therefore low-noise) foundations have been used at the Danish OWFs Sprogø and Nysted.

Noise-Mitigation Measures to Reduce the Transmitted Piling Noise

The German Federal Government is funding strategic research on the development and testing of noise-mitigation measures during pile driving. A sound-mitigation system “hydro sound damper” (HSD) was tested at the UK London Array OWF under offshore conditions at water depths of 15–18 m (Remmers and Bellmann 2013). The noise reduction achieved was 7–13 dB SEL and 7–15 dB peak SPL. The ESRa research project tested five different noise-mitigation systems in Lübeck Bay at 8.5 m depth, achieving significant reduction effects with all systems, with values between 7 and 9 dB in the broadband SEL (Wilke et al. 2012). Pehlke et al. (2013) successfully deployed and tested different “big bubble curtain” (BBC) configurations at the wind farm Borkum West II in water depths of 27–33 m, reporting a noise reduction of 9–13 dB in SEL and 10–17 dB in SPL with configuration BBC2. In 73% of the foundations, the piling noise was kept below the German SEL threshold value of 160 dB re 1 $\mu\text{Pa}^2\cdot\text{s}$, and it was always below 163 SEL re 1 $\mu\text{Pa}^2\cdot\text{s}$ and the SPL threshold value of 190 dB re 1 μPa peak to peak. Using the disturbance threshold of 144 dB re 1 $\mu\text{Pa}^2\cdot\text{s}$ SEL, the behavioral impact radius was calculated to be 15 km for unshielded ramming operations and 4.8 km with the BBC. Applying the noise-mitigation measure therefore reduced the impact area (and likely the number of animals affected) by 90% (Pehlke et al. 2013).

4 Conclusions

The mitigation measures taken in the reviewed countries suggest a general consensus that piling noise is potentially the most harmful impact to marine mammals in OWF projects, with the potential to cause auditory injury or behavioral disturbance and displacement. Construction noise can result in impacts up to several tens of kilometers away from the construction site with no noise-reduction techniques applied. The advantages and disadvantages of the different mitigation measures are described below.

Mitigation measures reducing noise, like the BBC, can significantly minimize the behavioral impact area and keep the auditory injury impact within a limited area around the sound source. However, it will not eliminate the impact. The applicability of this technique under challenging conditions such as greater depths and stronger currents than found in the areas tested to date and the effect of its use on construction schedules remains to be fully assessed.

Monitoring an exclusion zone with a delay to the commencement of piling on a marine mammal sighting is intended to reduce the risk of instantaneous auditory injury. It does not prevent behavioral disturbance and displacement and may not always prevent cumulative noise exposure (over whole piling events), leading to auditory injury. However, the exclusion zone that would have to be considered to avoid auditory injury may be beyond the scale of what can be effectively monitored when pile driving is conducted without any kind of noise-reducing methods. Furthermore, MMOs and PAM may not detect all animals present within the monitored zone, and PAM undertaken at times with low visibility will only be effective for vocalizing mammals and will therefore not be appropriate for baleen whales or seals.

Pingers, seal scarers, and soft starts, when employed as a mitigation measure, are also intended to reduce the risk of instantaneous auditory injury. They rely on the evocation of strong behavioral reactions to move animals away from the zone of impact rather than preventing behavioral impacts such as displacement and/or disturbance to normal activities. Brandt et al. (2013) showed that the deployment of a Lofitech seal scarer does have a deterrent effect on harbor porpoises and can therefore greatly reduce the risk of physical injury for porpoises during offshore piling. Nevertheless, animals can habituate to these devices, which would result in a decrease of the effectiveness of such devices over time. Furthermore, not all animals may respond, especially if other factors, such as food availability, may motivate the animals to stay within the impact zone.

Seasonal restriction of pile-driving activities, at times with high animal densities or at sensitive times for specific species, may be the only option in particularly sensitive areas where an OWF project would otherwise not go ahead because of predicted negative impacts on protected species. However, given the extensive future construction schedules, e.g., as for UK round 3 wind farms, such restrictions would likely render many projects unviable.

Low-noise emission foundations such as gravity-based designs or floating turbines, which basically do not or hardly require piling, are recommended whenever feasible but especially when animals are present in high numbers and in areas of particular importance to marine mammals. This solution would greatly reduce the need for any other marine mammal impact mitigation measures but may not be applicable at every OWF site.

All mitigation measures discussed above are based on the avoidance of instantaneous auditory injury, and they may even enhance the behavioral impact and displacement of animals. Unfortunately, very little is currently known about the individual or population consequences of auditory injury or disturbance/displacement. It is currently uncertain which impacts have more severe consequences for individuals and ultimately populations (auditory injury or displacement/disturbance) and it is likely that the balance will differ between species and sites. There are several planned initiatives aimed at reducing this uncertainty over the coming years (e.g., Offshore Renewables Joint Industry Programmes [ORJIP]) projects), but these will rely on empirical data being collected during future construction and therefore it is imperative that mitigation and monitoring at a site-specific level be geared toward gaining an understanding of these issues.

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Chapter 148
Discovery of Sound in the Sea: Resources for Educators, Students, the Public, and Policymakers

Kathleen J. Vigness-Raposa, Gail Scowcroft, James H. Miller, Darlene R. Ketten, and Arthur N. Popper

Abstract There is increasing concern about the effects of underwater sound on marine life. However, the science of sound is challenging. The Discovery of Sound in the Sea (DOSITS) Web site (http://www.dosits.org) was designed to provide comprehensive scientific information on underwater sound for the public and educational and media professionals. It covers the physical science of underwater sound and its use by people and marine animals for a range of tasks. Celebrating 10 years of online resources, DOSITS continues to develop new material and improvements, providing the best resource for the most up-to-date information on underwater sound and its potential effects.

Keywords Communication • Acoustics • Marine animals • Sound effects • Underwater sound

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1 Background to the Development of the Discovery of Sound in the Sea

The scientific community and the general public have become increasingly aware of and concerned about underwater sound (Nowacek et al. 2007; Southall et al. 2007; Popper and Hastings 2009; Ellison et al. 2012; Moore et al. 2012; Popper and Hawkins 2012). There is both an interest in learning about the sources and uses of underwater sound and a need for up-to-date peer-reviewed resources on the potential effects of sound on the ocean and its inhabitants. However, understanding the acoustics and related physics as well as the complexities of these phenomena in air versus water can be challenging. Underwater sound is a complex topic, and there is a shortage of resources available at an introductory level.

The primary goals of the Discovery of Sound in the Sea (DOSITS) are to provide a comprehensive resource, based on peer-reviewed science, for multiple user groups; to provide training opportunities for educators, policy makers, and the media; to reach the widest audience possible; and to inspire the next generation of scientific explorers. Another goal for the site is for it to serve as a resource that dispels popular myths, often found in the popular media or advocacy-based Web sites and materials. Content, such as the effects of sonar on marine life, is based on peer-reviewed publications and has undergone rigorous review by the DOSITS scientific advisory panel.

The DOSITS Web site has been designed to provide accurate scientific information on underwater sound at levels appropriate for all audiences, including the general public, K-12 teachers and students, college students, policy makers, and professionals in industry, education, and the media (Vigness-Raposa et al. 2008, 2012). The DOSITS Web site covers the physical science of underwater sound and how sound is used by people and marine animals for a wide range of tasks and behaviors from exploration to communication and survival in three main science sections. There are also three resource sections, with information designed for teachers, students, and the media. The site's three galleries focus on underwater sounds (Audio Gallery), scientific equipment (Technology Gallery), and acoustics-related research (Scientist Gallery).

The DOSITS Web site was launched in November 2002, but it has not been static either in content or in structure. The content undergoes major reviews twice annually and continues to grow with monthly updates and improvements as new scientific literature is published. Working with a professional Web design team, the DOSITS Web site was relaunched in March 2010 with a fresh "look and feel" that maintains functionality and content (Vigness-Raposa et al. 2012). The redesign included an interactive front page, an interactive Audio Gallery, and a redesigned Scientist Gallery.

The significance of the DOSITS resource is evident in the fact that the Web site has received approximately 63 million "hits" over its first 10 years, with Web traffic spiking during the 2010 relaunch and continuing to increase over the years (Fig. 148.1). In 2012, the DOSITS Web site saw a 20% increase in traffic over 2011, receiving over 10 million hits/year. This illustrates the level of public and professional education and scientific interest in this increasingly important topic and its value to the underwater acoustics community.

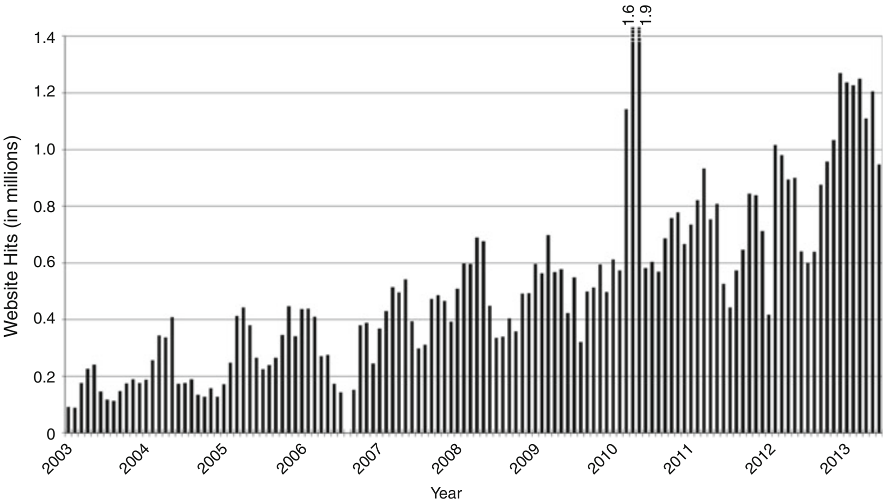

Fig. 148.1 The number of Web site "hits" (in millions) per month from January 2003 through June 2013

2 Overview of the DOSITS Web Site

The DOSITS Web site includes three major science sections: the Science of Sound in the Sea, People and Sound in the Sea, and Animals and Sound in the Sea. These three major sections include ~400 pages of content, which provide a thorough introduction to underwater acoustics, its many uses, and the appropriate level of concern regarding the potential effects on the environment with both basic level information and in-depth discussions of important science topics.

All DOSITS information is based solely on published peer-reviewed scientific research. Related research literature is continuously monitored for new information that is regularly added to the Web site content and resources, ensuring that the most up-to-date results are incorporated into the DOSITS resource. In addition, the Web site regularly undergoes a thorough review by a panel of four to eight scientific experts in each of the major topic fields to ensure the highest scientific accuracy and integrity.

The Science of Sound in the Sea section (http://www.dosits.org/science/science-summary/) provides a thorough introduction to the physical science of underwater sound. The Science of Sound in the Sea section includes such topics as sound movement, sound measurement, and the difference between sound in air and sound in water.

People and Sound in the Sea (http://www.dosits.org/people/peoplesummary/) includes information on the many important everyday activities that humans do in and on the ocean that depend on sound for success. Navigation, fishing, communication, and research and exploration are just a few examples of the tasks that require the use of underwater sound.

Animals and Sound in the Sea (http://www.dosits.org/animals/animalsandsound-summary/) includes information on how marine animals produce and receive sound and use sound to sense their surroundings, communicate, locate food, and protect themselves underwater. The Animals and Sound in the Sea section also includes an in-depth discussion on the current state of knowledge of the effects of underwater sound on marine mammals, fishes, and invertebrates.

As the DOSITS Web site has progressed, advanced level content that is appropriate for high-school physics classes and undergraduate and early graduate-level science classes has been added to each science section. These Advanced Topics are described in Section 4.

The DOSITS Web site also has three Galleries. The Audio Gallery (http://www.dosits.org/audio/) contains more than 100 underwater sounds from marine mammals, marine invertebrates, fishes, human activities, and natural phenomena. The Audio Gallery includes a flash-based interactive that displays pictures, videos, and audio files with spectrograms and waveform displays (see Section 3) as well as nonflash pages with background descriptions of the sound source and audio files in QuickTime and MP3 formats.

The Scientist Gallery (http://www.dosits.org/scientist/) highlights the cutting edge research of five renowned scientists in the field of underwater acoustics. Video clips of interviews with the scientists, along with accompanying transcripts, allow the users to learn what motivated the scientists to become acousticians and the educational and learning processes they underwent to become world-class researchers. The Scientist Gallery also includes pages describing their research as well as their biographies.

The Technology Gallery (http://www.dosits.org/technology/techsummary/) contains images and descriptions of the scientific and commercial equipment that is used by humans for everyday tasks. Because light is relatively opaque underwater and sound is transparent, sound must be used for a wide variety of tasks, from observing the seafloor and locating objects underwater to advanced research tasks such as measuring ocean currents and temperature.

In addition to the Galleries, there are three Resources sections. The Media Resources section (http://www.dosits.org/resources/media/) contains a frequently asked questions (FAQ) briefing designed to provide scientific answers to the most commonly asked questions about underwater sound and its effects on marine life. The Media Resources section also includes a facts and myths quiz that tests the reader's understanding of the complex topic of underwater sound, providing answers and links to pages on the DOSITS Web site for further information. In addition to these Internet resources, there is a 16-page booklet and a trifold brochure that are available in print and as downloadable PDF files on the Web site. These resources have recently been translated to languages other than English (see Section 5).

The Teacher Resources section (http://www.dosits.org/resources/teachers/) includes a list of helpful classroom resources along with classroom activities developed by K-12 educators and educational professionals. A recent update includes a complete and practical classroom instruction guide on *How To Build a Hydrophone* activity (http://www.dosits.org/resources/all/classroom/buildhydrophone/). The activity now includes detailed directions accompanied by photographs that outline the equipment to be used and demonstrates crucial steps as the hydrophone takes shape. In addition to classroom activities, PowerPoint presentations designed for classroom use of the Web site content are available for downloading. The Teacher Resources section also includes structured tutorials on the topics of the science of underwater sound, the technologies used with underwater sound, and the potential effects of underwater sound, both natural and anthropogenic, on marine life. These structured tutorials are designed as linear learning resources with progressively developed stages of knowledge, thereby guiding educators in the sequence of learning development for these three critical topics. The Student Resources section (http://www.dosits.org/resources/students/) also includes the structured tutorials.

3 Improvements to the Audio Gallery

The front page of the Audio Gallery includes a flash-based interactive that allows the user to efficiently select and move between sound sources (Fig. 148.2). This is done by selecting either the "Category" or "Taxonomy" radio button and using the provided drop-down menu. The Category drop-down menu includes Marine Mammals–Baleen Whales, Marine Mammals–Toothed Whales, Marine Mammals–Pinnipeds,

Picture:
A sei whale at the surface.A sei whale at the surface. Note the animal's long body- due to their body length, researchers usually only capture a picture of a sei whale's back (with {{dorsal fin}}), or its head, rarely both together. Image courtesy of the Woods Hole Oceanographic Institution and the NOAA Northeast Fisheries Science Center.

Fig. 148.2 A screen capture of the flash-based interactive of the Audio Gallery Web page (www.dosits.org/audio/) developed for the Discovery of Sound in the Sea (DOSITS) Web site relaunch in March 2010

Marine Mammals–Sirenians, Marine Invertebrates, Fishes, Other Natural Sounds, and Anthropogenic Sounds. Taxonomy refers to the Linnean system in biology commonly used for classifying animals based on anatomical similarities and ancestry. On DOSITS, the family levels are used, which is particularly useful for categorization and comparison of the vocalizations of fishes. Other natural and anthropogenic sounds are listed below the families.

The Audio Gallery interactive window was recently expanded to include a sound visualization tool that is launched when an audio file is selected for a particular sound source. When a sound of interest is selected in the interactive window, the sound is heard and the sound visualization tool displays a spectrogram and waveform within the interactive window. As the sound plays, a scroll bar reveals the spectrogram and waveform so that the viewer can simultaneously hear the sound and visually see the changes in the frequency and pressure components of the sound.

4 Expansion of Advanced Topics

Within the three major science sections, Advanced Topics are included that address the content that would be appropriate for high-school, undergraduate, and early graduate levels. Although the majority of the DOSITS Web pages do not include mathematical formulae and are written for a typical newspaper reader (8th-grade reading levels), Advanced Topics include mathematical formulae and advanced scientific principles that extend the reader’s understanding of related science concepts in physics, acoustics, biology, and even chemistry as appropriate. Sample topics include Introduction to Decibels, Scientific Method, Scientific Uncertainty, and Temporary Threshold Shift (TTS) Studies. As these titles suggest, Advanced Topics such as Scientific Method and Scientific Uncertainty are appropriate for many audiences, but some can also be quite specialized, such as TTS Studies.

Advanced Topics have recently been expanded to include new pages on hearing and impulsive and explosive sound sources. The new advanced sections on impulsive and explosive sound sources describe the acoustics of underwater explosions, which are significantly different from that of a coherent source like a fish finder or acoustic projector. How these differences in acoustics can change the effects experienced in the marine environment are also discussed.

The two new Advanced Topics pages on hearing focus on (1) how some vertebrate animals hear different components of sound and (2) advanced scientific descriptions of those sound components, including how sound can be characterized by particle motion, pressure, and intensity. Respectively titled What Components of Sound Are Used for Hearing? (http://www.dosits.org/animals/advancedtopics/componentsofsound/) and What Is Intensity? (http://www.dosits.org/science/advancedtopics/whatsintensity/), these sections focus on key sound components (pressure and particle motion) and clarify the relationships between intensity, pressure, and particle velocity. In addition, there is a new Advanced Topic that describes the evolution of hearing in odontocetes, with an animation that steps through the evolutionary phases.

5 Media Resources in Multiple Languages

It is recognized that the media have unique professional needs, with imminent publishing deadlines that benefit from efficient access to accurate scientific information. The DOSITS team appreciates that print resources at hand may be more useful for certain audiences than Internet Web pages. Therefore, in addition to the extensive content found on the DOSITS Web site, there is a 16-page educational booklet (http://www.dosits.org/resources/all/downloads/publications/booklet/) and a trifold brochure (http://www.dosits.org/resources/all/downloads/publications/brochure/) that are available in print and as downloadable PDF files on the Web site. The educational booklet is designed for readers that need more comprehensive information in print format. It mirrors the content sections on the Web site but pares down the information to those components deemed essential for understanding the key principles of science topics and associated issues. The trifold brochure is designed to provide a broad-brush overview of the Web site and its 400+ pages of content, with colorful graphics highlighting major features but only the most necessary supporting text. As a road map to locate focal points of information on the DOSITS Web site, the brochure is a means of introducing and encouraging further exploration of the Web site pages.

English is the current language on the Web site, but the DOSITS team recognizes the need to continue to strive to reach as many audiences as possible, particularly in light of our goal to meet the needs of K-12 students. To reach a more diverse audience, print resources have been translated into Spanish and French and reviewed by native speakers. The Spanish booklet has been distributed to educational professionals within Spanish-speaking communities as well as to Mexican commercial vessel operators who conduct whale-watching and fishing tours. The French trifold brochure was distributed at the DOSITS 10th anniversary celebratory symposium held during the International Congress on Acoustics/Acoustical Society of America meeting in Montréal, Canada.

6 Looking Forward After 10 Years of DOSITS

After being online for 10 years, DOSITS continues to achieve its goals of providing comprehensive resource and training opportunities for many user groups. The DOSITS team looks forward to expanding our content on seismic exploration and offshore renewable energy technologies as well as on studies of marine animal distribution and ocean noise budgets in the polar regions as global warming opens these regions to new anthropogenic activities (Moore et al. 2012). The site continues to evolve, reaching the widest audience possible with translations in Spanish and French and encouraging foreign speakers to collaborate with the DOSITS team to further expand resources into other languages. The authors seek to inspire the next generation of scientific explorers with more Advanced Topics, providing them with an overview of the substantial foundation of scientific research that currently exists in the field of underwater acoustics on which they can build.

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Chapter 149
Effects of Previous Acoustic Experience on Behavioral Responses to Experimental Sound Stimuli and Implications for Research

Irene K. Voellmy, Julia Purser, Stephen D. Simpson, and Andrew N. Radford

Abstract Ambient noise differs considerably between habitats. Increased ambient noise can affect the physiology and behavior in a variety of taxa. Previous acoustic experience can modify behavior and potentially affect research conclusions in natural and laboratory environments. Acoustic conditions should thus be accounted for, especially in experiments involving experimental sound stimuli. Methods sections should contain acoustic specifications, and a consensus should be achieved over which measurements to include for comparability between researchers. Further investigation of how previous and repeated exposure to sound affects behavior and research conclusions is needed to improve our knowledge of acoustic long-term effects in animal welfare and conservation.

Keywords Holding conditions • Aquarium noise • Anthropogenic noise • Ambient noise • Carryover

1 Ambient Noise Level Variability

Ambient noise varies greatly in terrestrial and aquatic environments. This variability arises from different sound-propagation characteristics modified by vegetation cover and density, substrate conditions, and abiotic and biotic sound sources (e.g., Marler and Slabbekoorn 2004; Popper and Hastings 2009a). Vegetation is a key factor that degrades and attenuates sound with increasing biomass and density (Martens 1980; Richards and Wiley 1980). Substrate characteristics mediate the amount of

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sound reflected or absorbed (e.g., Slabbekoorn et al. 2007). Abiotic sounds, such as those caused by rain, water currents, wind, earthquakes, and avalanches (e.g., Popper and Hastings 2009a), and biotic sound sources actively and passively emitted by living organisms (e.g., Bradbury and Vehrencamp 1998; Amorim 2006; Goerlitz et al. 2008) mediate the amount of signal interference and masking (e.g., Greenfield 1994; Bradbury and Vehrencamp 1998).

In terrestrial habitats, it has been long recognized that acoustic environments shape sensory ecology and evolution. In birds, for instance, song structures within and between species change with environmental conditions due to habitat-specific sound propagation and naturally occurring ambient noise (Morton 1975; Richards and Wiley 1980; Slabbekoorn and Smith 2002). Considerable work has investigated how acoustic experience can affect singing and mate choice behavior in birds (Riebel 2003; Marler and Slabbekoorn 2004; Woolley 2012), and previous acoustic experience has also been shown to modify reproductive behavior in crickets (*Gryllidae*; Wagner et al. 2001; Bailey et al. 2010).

Increasingly sophisticated underwater sound-recording equipment has moved research on underwater "soundscapes" forward and revealed considerable acoustic differences between and within aquatic habitats (Amoser and Ladich 2010; Radford et al. 2010; McWilliam and Hawkins 2013). A recent study has shown that previous acoustic experience can modify the behavioral response to sound stimuli in coral reef fish larvae (Simpson et al. 2010), organisms that have been shown to use acoustic cues to find their settlement sites (e.g., Simpson et al. 2005) and differentiate between different coral reef habitats (Radford et al. 2011). Moreover, a rapidly growing literature shows that increased noise levels can affect the physiology and behavior in animals of all taxa, including humans (e.g., Popper 2003; Barber et al. 2010; Radford et al. 2012).

The above examples indicate that a previous acoustic experience most likely also affects the physiology and behavior in research experiments. Responses to experimental stimuli may be modified by a variety of mechanisms, including increased hearing threshold levels as a physiological consequence to exposure to elevated sound levels (e.g., Codarin et al. 2009; Gutscher et al. 2011) or habituation or sensitization due to repeated previous exposure to specific sound sources or increased sound levels (Bejder et al. 2009). It is important to note that not only average sound levels of ambient noise can affect animal physiology and behavior but also sound level fluctuations and their predictability and frequency components (De Boer et al. 1989; Popper and Hastings 2009b).

2 Acoustic Variability in Captive Environments

Animals kept in captivity as pets, in zoos, or for food production and research are exposed to highly variable acoustic environments (Morgan and Tromborg 2007). Sound sources in captive environments range from continuous low-frequency noises caused by room ventilation and, in the case of aquatic animal facilities, by aquarium water filtration and aeration to ultrasonic sources arising from electronic equipment. In addition to continuous constant noise, sudden unpredictable noises can occur arising from maintenance activities (Milligan et al. 1993; Morgan and Tromborg 2007).

Elevated noise levels and the sudden onset of noises in animal facilities have been shown to elicit physiological responses such as increased blood pressure, plasma cortisol, heart rate, and metabolic rate (reviewed by Morgan and Tromborg 2007; Castelhano-Carlos and Baumans 2009). Sudden noises can also elicit behavioral responses such as increased agitation or startle responses, with potentially fatal consequences (Marai and Rashwan 2004; Leong et al. 2009; Gronquist and Berges 2013). Increased noise levels during the day caused by human activities can also lead to activity shifts of nocturnal animals to become more diurnal (reviewed by Morgan and Tromborg 2007).

Therefore, it is reasonable to predict that acoustic conditions in animal facilities may affect experimental findings. Dallman et al. (1999) showed that noise arising from nearby construction sites affected studies focusing on stress hormones in rodents. Because stress responses are involved in and affect a variety of physiological and behavioral mechanisms (Wendelaar Bonga 1997; Charmandari et al. 2005), previous exposure to elevated noise levels can have detrimental effects on a wide range of laboratory studies addressing questions beyond responses to experimental noise stimuli. Thus, controlling ambient-noise levels and minimizing the occurrence of sudden noises are not only issues of animal welfare but are also important for research design and planning.

Despite these known effects, acoustic environments in laboratories and animal facilities have not been considered systematically as a potential source of modification in experiments and are not monitored and reported in a standardized way. This is in contrast to light, temperature, feeding regimens, and elements of environmental enrichments (Baldwin et al. 2007; Turner et al. 2007). Recent studies showing the effects of acoustic test conditions on rat spatial learning and memory (Prior 2002, 2006) emphasize the necessity of reporting acoustic conditions in experimental areas, but ambient noise levels in holding cages have not been specified and as a consequence, any previous acoustic experience of the animals has not been monitored.

3 Implications for Research

The above examples illustrate the necessity of taking previous acoustic exposure into account, especially when designing and conducting research on the impact of experimental acute, repeated, or chronic sound stimuli as well as for experiments conducted in natural and laboratory conditions in general. It is therefore important to include in the Methods section of papers and research reports specifications of the noise levels and acoustic characteristics of natural habitats and laboratory holding conditions that animals were exposed to before experiments were conducted. To achieve comparability of acoustic quantifications, it is very important to find a consensus on which measurements to include to characterize the sufficiently relevant acoustic features (see also Popper and Hastings 2009b). Ideally, these measurements should include not only average noise levels but also frequency distributions using spectral level analyses and descriptions of noise level fluctuations or sound impulsiveness, such as counts of noise peaks within a given time frame; kurtosis, a statistical measure to quantify the extent waveform amplitudes deviate from a normal distribution over the duration of a signal; or the amount of sound above 50, 75, and 90% of the sound energy.

Clearly, more work is needed to investigate the effects of previous acoustic experience and exposure to different ambient noise levels on the physiology and behavior of animals (see Chapter 111 by Radford et al). However, testing animals at acoustically different field sites applying identical test procedures may be logistically difficult to conduct. Thus, laboratory environments could serve as highly valid alternatives because previous exposure to sound is highly controllable and acoustic environments differing in particular acoustic features, such as noise levels and fluctuations, could be specifically designed and their effects explored. This could be achieved by using different holding tank setups, one of which is designed to minimize filter and aerator vibration noise transmission into the tank (as in Voellmy 2013). Because these laboratory experiments are focusing on the previous experience of different ambient noise levels, principles of the effects found in these studies, for instance, indications of habituation or sensitization, may also apply to natural scenarios.

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Chapter 150
Assessing the Effectiveness of Ramp-Up During Sonar Operations Using Exposure Models

Alexander M. von Benda-Beckmann, Paul J. Wensveen, Petter H. Kvadsheim, Frans-Peter A. Lam, Patrick J.O. Miller, Peter L. Tyack, and Michael A. Ainslie

Abstract Ramp-up procedures are used to mitigate the impact of sound on marine mammals. Sound exposure models combined with observations of marine mammals responding to sound can be used to assess the effectiveness of ramp-up procedures. We found that ramp-up procedures before full-level sonar operations can reduce the risk of hearing threshold shifts with marine mammals, but their effectiveness depends strongly on the responsiveness of the animals. In this paper, we investigated the effect of sonar parameters (source level, pulse-repetition time, ship speed) on sound exposure by using a simple analytical model and highlight the mechanisms that limit the effectiveness of ramp-up procedures.

Keywords Ramp-up • Soft start • Mitigation • Killer whales • Sonar

1 Introduction

Ramp-up (or soft-start) procedures are commonly used to mitigate the impact of sound on marine mammals (David 2006; Weir and Dolman 2007; Compton et al. 2008; Dolman et al. 2009). Several navies have adopted ramp-up procedures in an

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attempt to mitigate the effects on marine mammals of sonar used in antisubmarine warfare (Dolman et al. 2009). The idea of ramp-up procedures is that the gradual increase in sound source level offers animals near the source the opportunity to swim away and thus potentially decreases the risk of adverse effects once the source reaches full power. Although this procedure is often adopted as a common-sense approach (e.g., Joint Nature Conservation Committee 2004; International Whaling Commission 2006), studies that quantify the effectiveness of ramp-up procedures are currently lacking. Because no theoretical or experimental studies demonstrating that ramp-up procedures are beneficial have been conducted, the effectiveness of ramp-up procedures for risk mitigation is still under debate (Stone and Tasker 2006; Weir and Dolman 2007; Dolman et al. 2009).

2 Ramp-Up Effectiveness

von Benda-Beckmann et al. (2014) investigated the effectiveness of ramp-up procedures by modeling the sound exposure of killer whales caused by a moving sonar. They considered a naval sonar operation that was preceded by different ramp-up schemes and the reduction in the area over which adverse effects were predicted to occur was quantified. The adverse effects assessed here were temporary and permanent shifts in hearing threshold, changes that have been interpreted as injury by some regulators. The ramp-up procedure before a sonar operation was designed to minimize the impact on killer whales. An animal behavior model was based on avoidance responses observed with free-ranging killer whales responding to sonar sounds during controlled exposure experiments (Miller et al. 2012, 2014). Based on these observed responses, modeled animals were assumed to move sideways from the source track line once the sound pressure level (SPL) exceeded a threshold level ($\mathrm{SPL}_{\mathrm{avoid}}$). To investigate the effect of responsiveness on the model outcome, this $\mathrm{SPL}_{\mathrm{avoid}}$ was varied within the range of observed levels for which killer whales responded to an approaching sonar.

The simulation results in von Benda-Beckmann et al. (2014) indicate that ramp-up procedures can reduce the risk of receiving sound exposure sufficient to induce hearing threshold shifts (temporary [TTS] or permanent [PTS]) in marine mammals. However, the predicted effectiveness of the ramp-up procedure was found to depend strongly on the assumed response threshold and to vary with ramp-up duration. The dependency on ramp-up duration showed four typical relationships depending on the responsiveness (i.e., how likely animals were to respond at any given $\mathrm{SPL}_{\mathrm{avoid}}$). These four typical relationships are illustrated schematically in Fig. 150.1.

It was found that for the killer whales in von Benda-Beckmann et al. (2014) that extending the duration of the ramp-up procedure beyond a few minutes did not add much to the predicted reduction in hearing impact on killer whales. The main factors that limit the effectiveness of the ramp-up procedure in a typical antisubmarine warfare scenario are the combination of high source level, a rapidly moving sonar source, and long silences between consecutive sonar transmissions. The mechanisms that determine the effectiveness of ramp-up procedures are illustrated in this paper by considering a simplified exposure model for a moving sonar source.

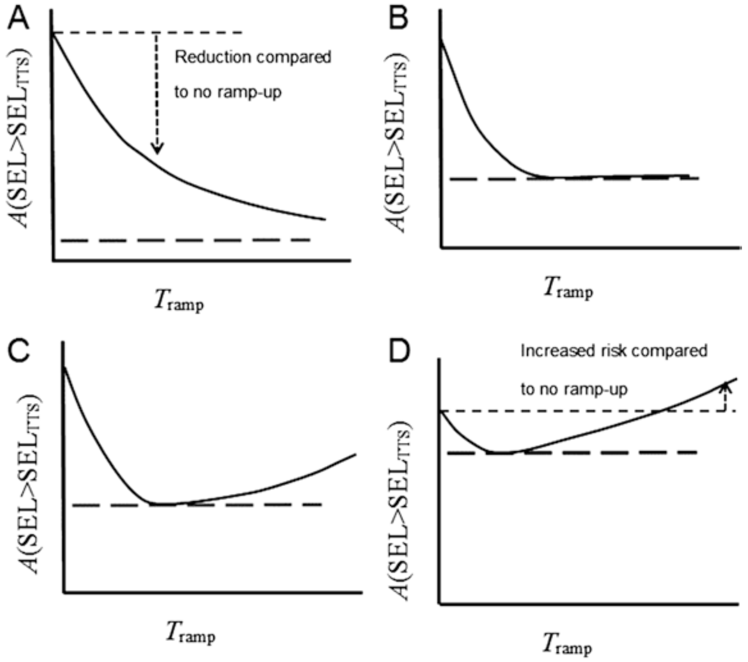

Fig. 150.1 Schematic representation of the relationship between the affected area [$A(\mathrm{SEL}>\mathrm{SEL}_{\mathrm{TTS}})$; SEL, sound exposure level; TTS, temporary threshold shift] where the animals would receive a high enough exposure to cause hearing thresholds shifts as a function of ramp-up duration (T_{ramp}). Four different trends are distinguished in the study by von Benda-Beckmann et al. (2014) depending on the responsiveness of the animals. (**a**) For very responsive animals, increased ramp-up duration continues to decrease the affected area. (**b**) For less responsive animals (i.e., those that respond at a higher sound pressure level [SPL]), the risk of the operation increases, the ramp-up duration becomes less effective, and the affected area is only increased to some level. (**c**) For even less responsive animals, long-duration ramp-up procedures may result in an increased risk because transmissions during ramp-up procedures carry a risk of exposing the animals without being effective at mitigating the full-power operation. (**d**) In extreme cases where a large fraction of the animal population fails to respond to previous sonar transmissions and for sensitive species, the number of animals at risk of harmful effects may increase for long-duration ramp-up procedures compared with no ramp-up procedures. Gray dashed lines indicate the intrinsic risk during the full-power operation that cannot be mitigated using ramp-up procedures

2.1 Mechanisms Determining Ramp-Up Effectiveness

A Simple Exposure Model

In the case of a moving sonar source, the highest risk for an animal to experience high sound exposure levels (SELs) is along the future track line of the ship (Ainslie and von Benda-Beckmann 2013). To estimate the amount of time that an animal requires to reach a safe distance, an analytical solution is used that estimates the probability of a TTS for any given cross-range distance (*d*) from the track line

(Ainslie and von Benda-Beckmann 2013). The distance ($d_{\mathrm{TTs,cum}}$) at which a stationary animal receives a cumulative SEL ($\mathrm{SEL}_{\mathrm{cum}}$) equal to the TTS SEL ($\mathrm{SEL}_{\mathrm{TTS}}$) for a source passing by with a ship speed (v_{s}) is estimated using Ainslie and von Benda-Beckmann (2013)

$$d_{\mathrm{TTS,cum}} = \pi \frac{D \cdot 10^{\mathrm{SL}/10} \left(..\mathrm{Pa}^2 \mathrm{m}^2 \right)}{v_s 10^{\mathrm{SEL}_{\mathrm{TTS}}/10} \left(..\mathrm{Pa}^2 \mathrm{s} \right)} \tag{150.1}$$

where D is the sonar source duty cycle and SL is the source level. For small approach distances (closest points of approach [CPAs]), the contribution of the closest transmission dominates the sound exposure experienced by the animal. Here the risk of TTS is estimated by assuming that the transmission occurs at the CPA ($d_{\mathrm{TTS,CPA}}$)

$$d_{\mathrm{TTS,CPA}} = 10^{\left(\mathrm{SL}\ \ \mathrm{SEL}_{\mathrm{TTS}} + 10 \log\left(T_{\mathrm{sig}} / 1\ \mathrm{s}\right)\right)/20} \quad \mathrm{m} \tag{150.2}$$

where T_{sig} is the signal duration, which is related to the pulse-repetition time (PRT) and D by $T_{\mathrm{sig}} = \mathrm{PRT} \cdot D$. The lateral distance at which an animal receives a cumulative exposure equal to TTS ($d_{\mathrm{TTS,safe}}$) is then the maximum of Eqs. 150.1 and 150.2

$$d_{\mathrm{TTS,safe}} = \max d_{\mathrm{TTS,cum}}, d_{\mathrm{TTS,CPA}} \tag{150.3}$$

We consider an animal responding when it avoids the source by moving in a direction perpendicular to the track line, which is similar to how killer whales are observed to respond to an approaching sonar (Miller et al. 2012). The time it takes for an animal starting on the track line (i.e., at highest risk) to move to safe distance (T_{safety}) is then estimated using

$$T_{\mathrm{safety}} = \frac{d_{\mathrm{TTS,safe}}}{v_{\mathrm{m}}} \tag{150.4}$$

where v_{m} is the speed of the animal.

The amount of time available for an animal to avoid an approaching sonar source depends on the speed of the approaching vessel and the distance at which animals initiate an avoidance response (R_{avoid}). Suppose an animal starts avoiding the source at a received level of $\mathrm{SPL}_{\mathrm{avoid}}$ and the sonar is transmitting at a specific SL, the warning time of the signal ($T_{\mathrm{warn,sign}}$) is estimated as (assuming spherical spreading)

$$T_{\mathrm{warn,sign}} = \frac{R_{\mathrm{avoid}}}{v_{\mathrm{s}}} = \frac{10^{\frac{\mathrm{SL} - \mathrm{SPL}_{\mathrm{avoid}}}{20}}}{v_{\mathrm{s}}} \mathrm{m} \tag{150.5}$$

When we further consider that animals cannot be warned if the warning time (T_{warning}) is less than the PRT, the T_{warning} becomes

$$T_{\mathrm{warning}} = \begin{cases} T_{\mathrm{warn,sig}}, \# x0026; T_{\mathrm{warn,sig}} \geq PRT \\ 0, \# x0026; T_{\mathrm{warn,sig}} < PRT \end{cases} \tag{150.6}$$

The affected distance from the track line (d_{TTS}) within which animals are at risk of being exposed to $\mathrm{SEL} > \mathrm{SEL}_{\mathrm{TTS}}$ because they respond too late is then

$$d_{\mathrm{TTS}} = \max 0, v_{\mathrm{m}} \cdot \left(T_{\mathrm{safety}} - T_{\mathrm{warning}} \right) \tag{150.7}$$

In this simplified model, the SL determines the risk of TTS imposed on the animal. It also determines how far ahead of the sonar the animals will be warned. At low SLs, the risk of TTS is low, but signals transmitted at these SLs are also inefficient at warning animals. High SLs increase the distance at which an avoidance response is elicited but also increase the sound exposure received by animals.

2.2 Limiting Factors in Ramp-Up Effectiveness

Figure 150.2 shows the d_{TTS} at which whales are at risk of TTS for a wide range of sonar operational SLs and $\mathrm{SPL}_{\mathrm{avoid}}$ values and for PRTs of 3, 10, 30, and 100 s. Figure 150.2 indicates a sudden increase in d_{TTS}, which occurs at the point where

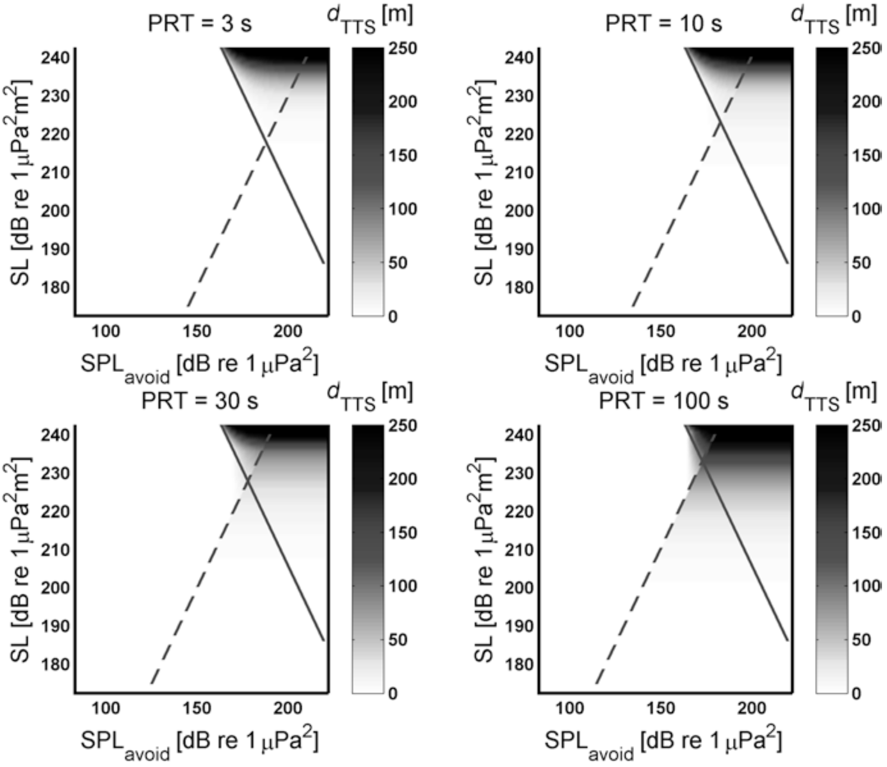

Fig. 150.2 Cross-range distance (d_{TTS}) from the sonar track line (gray scale) in which animals were exposed to a cumulative SEL>195 dB re 1 μPa^2.s (representative for midfrequency species; Southall et al. 2007) as a function of an assumed avoidance threshold ($\mathrm{SPL}_{\mathrm{avoid}}$) for pulse-repetition times (PRTs) of 3, 10, 30, and 100 s. A ship speed (v_s) of 10 m/s and animal swim speed of 0.5 m/s were used in this example. Solid lines indicate points where the warning time equals the time it takes for a warned animal to swim to a safe distance from the track line ($T_{\mathrm{warning}} = T_{\mathrm{safety}}$). Dashed lines dividing the 2 sections indicate where the T_{warning} equals the PRT of the signal ($T_{\mathrm{warning}} = \mathrm{PRT}$). SL, source level

$T_{\text{warning}} = T_{\text{safe}}$. Animals with low $\text{SPL}_{\text{avoid}}$ values will start avoiding the source earlier, resulting in a reduced sound exposure compared with a high $\text{SPL}_{\text{avoid}}$. For lower SLs, the affected area d_{TTS} drops because the safety distance (Eq. 150.4) is small and there is little risk of TTS. For a high SL and high $\text{SPL}_{\text{avoid}}$, the T_{warning} is insufficient for animals to move to a safe distance. The high d_{TTS} at higher SL therefore shows the risk inherent to an operation that cannot be mitigated using a ramp-up procedure because even the operational SL itself is not high enough to warn unresponsive animals in time. This determines the extent to which the risk of the operation can be reduced by using a ramp-up procedure (Fig. 150.1).

The effect of the PRT is also notable in Fig. 150.2. When the PRT is larger than the T_{warning}, transmissions do not stimulate animals to avoid them. For a higher PRT, there is an increased risk of TTS for a lower SL because the ship moves out of the region where it warned animals during previous transmissions.

3 Discussion

Ramp-up procedures are initiated before sonar operations by several navies with the aim of reducing the impact of sonar sound on marine mammals (Dolman et al. 2009). Using sound exposure models, von Benda-Beckmann et al. (2014) found that ramp-up procedures can reduce the area in which animals are exposed to levels high enough to induce hearing threshold shifts. However, the effectiveness depends on how responsive animals are to the sonar sound, which is likely to depend on the SPL received by the animal but also on the behavioral context of the animals (Southall et al. 2007; Ellison et al. 2012; Miller et al. 2012).

von Benda-Beckmann et al. (2014) found that the main factors limiting the effectiveness of ramp-up procedures in a typical antisubmarine warfare scenario are the combination of a high SL, a rapidly moving sonar source, and long silences between consecutive sonar transmissions. These lead to an intrinsic risk during the operation where the sonar is operated at full power that cannot be mitigated using ramp-up procedures.

In this paper, we illustrated the basic mechanisms that limit the effectiveness of ramp-up procedures by considering a simplified exposure model. The inherent risk of sonar transmitting at an operational SL is caused by animals failing to respond in time to move to a safe distance from the approaching sound source (see Fig. 150.2). This sets a lower limit for the affected area that can be realized by a ramp-up procedure for moving sources and limits the effectiveness of long ramp-up durations (see Fig. 150.1). For lower SL ramp-up transmissions, there is little risk involved by transmitting these pings, but the ability to mitigate is limited if they provide too little warning time for animals to move out of the way of the sonar. High SL ramp-up transmissions (>210 dB re 1 $\mu\text{Pa}^2\text{m}^2$) provide more warning time but start to carry their own risk that cannot be mitigated by previous transmissions of similar SLs (Fig. 150.2). This problem can limit the effectiveness of ramp-up procedures and can even increase the risk of TTS with increasing ramp-up duration.

Sound exposure modeling approaches combined with observations of how animals respond to an anthropogenic sound source provide the opportunity to quantify the effectiveness of mitigation measures such as ramp-up procedures. The approach presented here and in von Benda-Beckmann et al. (2014) can be used to evaluate and optimize ramp-up procedures for different sonar types but also for other activities that involve intense sound sources such as seismic surveys or pile driving.

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Chapter 151
Mapping the Acoustic Soundscape off Vancouver Island Using the NEPTUNE Canada Ocean Observatory

Carrie C. Wall Bell, Rodney A. Rountree, and Francis Juanes

Abstract NEPTUNE Canada is a cabled ocean observatory system containing five nodes located in the northeast Pacific Ocean. Using passive acoustic data recorded at two nodes (Folger Passage Deep and Barkley Canyon Axis) between June 2010 and May 2011, we sought to quantify the levels of vessel traffic and the occurrence of biological sounds to determine the potential impact of anthropogenic sound in masking acoustic communication. The results from a comparison of the relative amplitude and occurrence of low-frequency biotic sounds to broadband sounds resulting from vessel traffic are presented. Additional contributions to the marine soundscape from self-generated instrument noise are discussed.

Keywords Passive acoustics • NEPTUNE Canada • Marine soundscape • Northeast Pacific • Anthropogenic noise

1 Background

Elevated anthropogenic noise in marine soundscapes and their potential to decrease the communication efficacy of marine organisms is of increasing global concern. In the northeast Pacific, recent modeling studies have outlined areas of excessively

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high cumulative sound exposure levels from vessels (Erbe et al. 2012). Yet baseline levels of large-scale ambient noise are limited (Urick 1986; Andrew et al. 2002; Hildebrand 2009). Therefore, there is a strong need for continued research of sounds impacting deep-sea marine ecosystems that are particularly vulnerable to increasing anthropogenic noise (e.g., McDonald et al. 2006), especially with respect to the importance of biological sound production (Slabbekoorn et al. 2010). The implementation of cabled ocean observatory systems such as the North East Pacific Time-series Undersea Networked Experiment (NEPTUNE) Canada (Favali and Beranzoli 2009; Barnes et al. 2011) provide potentially ideal platforms to conduct long-term passive acoustic research on the marine soundscape (Wall et al. 2014).

The goal of this paper is to quantify the levels of biological sounds and vessel traffic above the ambient noise to determine the potential impact of anthropogenic sound in masking the communication of marine organisms using passive acoustic data collected at the NEPTUNE Canada Ocean Observatory over a 1-year period.

2 NEPTUNE Canada Ocean Observatory

NEPTUNE Canada, part of the Ocean Networks Canada Observatory, is a cabled ocean observatory system containing five nodes located in the northeast Pacific Ocean (www.neptunecanada.ca). A suite of data is collected at each node to characterize the chemical, geological, physical, and biological properties of the surrounding ocean environment. In particular, passive acoustic data are recorded at two nodes, Folger Passage Deep (100 m depth) and Barkley Canyon Axis (985 m depth), located in Barkley Sound. Acoustic files were recorded continuously at both nodes at a 96-kHz sample rate. These systems incorporated Naxys ethernet hydrophones (Folger Passage Deep: −171 re 1 V/μPa with a 20-dB gain; Barkley Canyon Axis: −179 dB re 1 V/μPa with a 20-dB gain; NAXYS Technology). Both hydrophones were only calibrated to 10 kHz. Therefore, despite accounting for the calibration coefficient, the amplitude measurements remain relative and incomparable between the nodes. Files were stored in 5-min segments, producing 12 files/h.

The long-term soundscape is displayed as a composite spectrogram in which 100-Hz resolution fast Fourier transforms (FFTs) are applied to each file and then placed together chronologically to create an image comprising the duration of data collected at both nodes from 26 June 2010 to 1 May 2011. To reduce processing time, a subset of 1 file recorded every 30 min was incorporated in this analysis, resulting in a total of 14,144 files from Folger Passage Deep and 11,933 files from Barkley Canyon Axis.

From the values calculated for the FFT in each file, three frequency bands were extracted and averaged to identify potential noise from vessel traffic and biological sound production, namely, soniferous fish and marine mammals (100–2,000 Hz; band 1); potential noise from vessel traffic and marine mammal sounds (2,500–10,000 Hz; band 2), and ambient noise (24,000–27,000 Hz; band 3). Band 3, which served as a baseline, was subtracted from bands 1 and 2 in each file to determine the relative increase in amplitude of biotic and abiotic sounds and thus their contribution to the marine soundscape. Results were binned hourly and monthly to determine diel and seasonal variability.

3 Acoustic Soundscape

Composite spectrograms calculated for the Folger Passage Deep and Barkley Canyon Axis nodes are illustrated in Fig. 151.1. Noise associated with instrumentation on both nodes was consistently recorded. The echo sounder located on the Folger Passage Deep node emitted high-amplitude broadband pulses visible in the composite spectrogram from 28 to 48 kHz. However, pulses were present down to 1 kHz in individual files. A narrowband tone at 33 kHz was present in all the Barkley Canyon Axis files. This noise is from general instrument operation. Broadband (1–48 kHz) click trains from sonar and 900-Hz tones from the pan/tilt video camera located on this node were also consistently recorded. Due to their short duration, these sounds were averaged out and are not visible in the composite spectrogram; however, they provide additional noise to the environment and potential interference for biological communication.

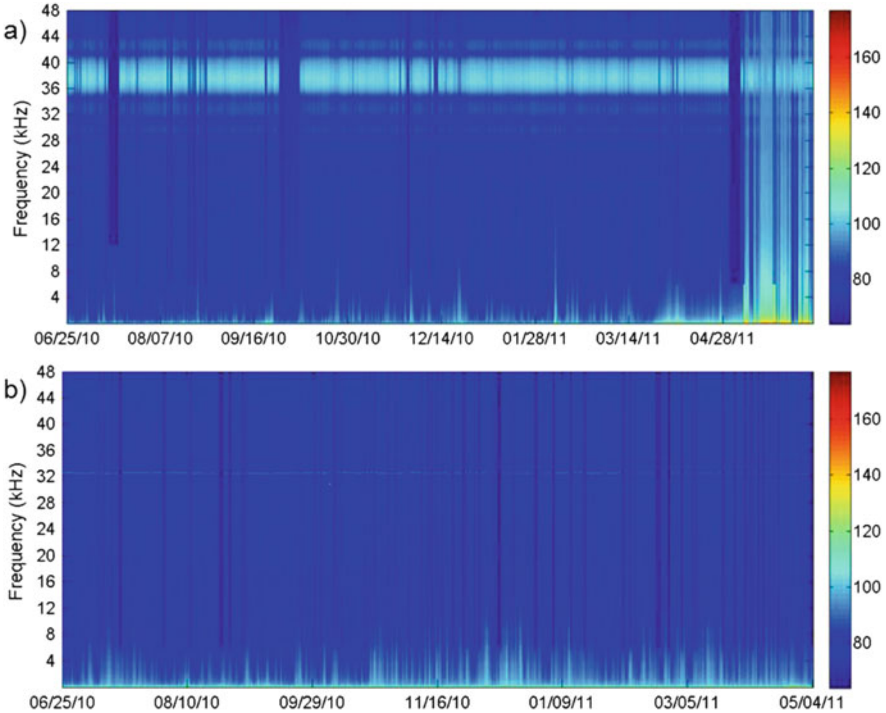

Fig. 151.1 Composite spectrograms of 100-Hz resolution fast Fourier transforms (FFTs) calculated for the NEPTUNE Canada nodes at Folger Passage Deep (**a**) and Barkley Canyon Axis (**b**). Values shown are relative and not directly comparable between the 2 nodes

3.1 Folger Passage Deep

There was no significant hourly difference in amplitude for sounds produced within band 1 or band 2 (Fig. 151.2a). However, amplitude variation within each hour was consistently high for band 1 (±3.5–3.8 dB) and band 2 (±2.1–2.2 dB). Amplitudes in band 1 and band 2 were more variable within (±0.2–3.0 dB) and between months (Fig. 151.2b). Amplitude increased significantly from September to December 2010, with April 2011 containing a significantly higher amplitude than all other months. The increase in April is attributed to electrical noise associated with the hydrophone housing leaking toward the end of the study period. Band 1 had consistently higher hourly and monthly amplitudes compared with band 2. Both bands were highly correlated ($R^2=0.93$), whereas each band showed a very low correlation to band 3 (band 1 and band 3, $R^2=0.24$; band 2 and band 3, $R^2=0.32$).

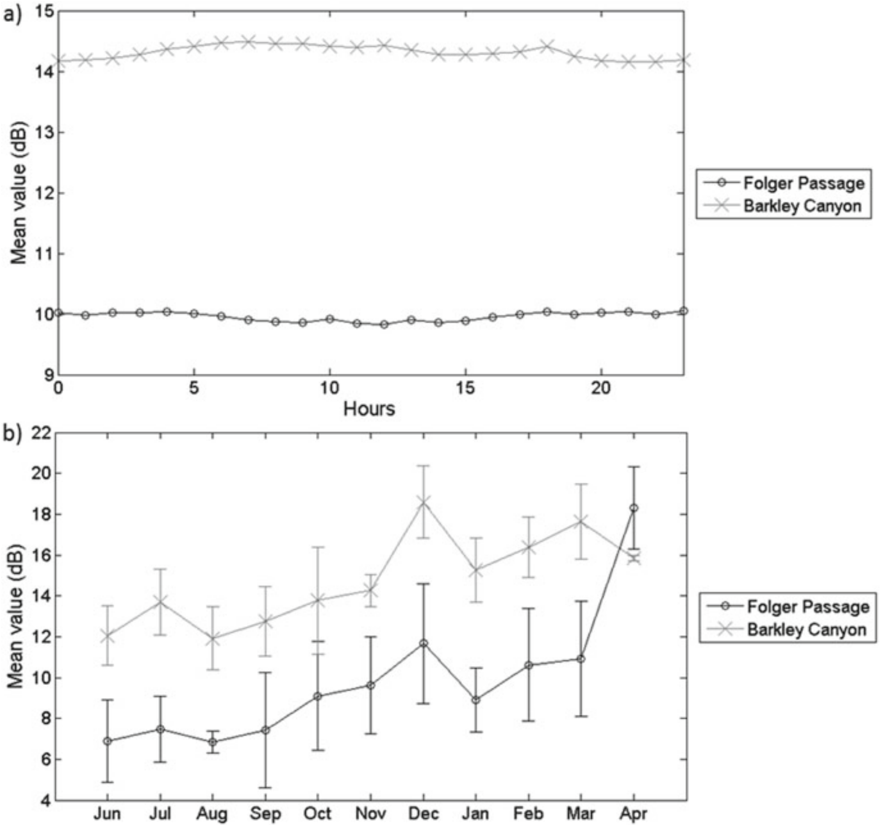

Fig. 151.2 Amplitudes extracted from band 1 for Folger Passage Deep and Barkley Canyon Axis binned by hour (means; **a**) and by month (means ± SD; **b**). Values shown are relative and not directly comparable between the 2 nodes. For clarity, error bars are not shown for the hourly bin

3.2 Barkley Canyon Axis

Similar to Folger Passage Deep, the amplitude did not vary significantly by hour for either band, whereas monthly values were more variable (see Fig. 151.2). Amplitude variation within each hour was consistently high (±2.1–2.7 dB). Increasing amplitude was again observed from September to December 2010. Amplitude variation within each month ranged widely (±0.1–2.6 dB). Band 1 had a consistently higher amplitude (hourly and monthly) compared with band 2. Both bands were highly correlated ($R^2 = 0.96$), whereas each band was less correlated to band 3 (band 1 and band 3, $R^2 = 0.46$; band 2 and band 3, $R^2 = 0.45$).

4 Conclusions

This paper examined the marine soundscape off west Vancouver Island in the northeast Pacific using passive acoustic data collected at two nodes within the NEPTUNE Canada cabled ocean observatory system. We sought to quantify the contribution of biotic and abiotic sounds to ambient noise over time using three frequency bands encompassing potential fish and marine mammal sounds and vessel traffic (band 1), marine mammal sounds and vessel traffic (band 2), and ambient noise (band 3).

The high-correlation average values within band 1 and band 2, corrected for ambient noise, suggests that low-frequency (<2-kHz) sounds, such as those made by fish, do not contribute greatly to the acoustic soundscape due to the infrequent occurrence and/or short duration of such sounds. Therefore, broader band and longer duration sounds resulting from marine mammals and passing vessels dominate frequencies below 10 kHz. Sounds from humpback whales (*Megaptera novaeangliae*) in June, October, November, and December; from pinnipeds (Otariidae) in August, September, and October; and from killer whales (*Orcinus orca*) in February have been documented at Folger Passage Deep (C. Pomerleau, personal communication). At Barkley Canyon Axis, sounds from baleen whales, humpback whales, and fin whales (*Balaenoptera physalus*) from September through December; from Pacific white-sided dolphins (*Lagenorhynchus obliquidens*) in August and September; and from killer whales in March were observed (C. Pomerleau, personal communication). Marine mammal calls can range from 50 Hz to 10 kHz (Mellinger et al. 2007). Similarly, harmonics associated with vessel traffic can reach beyond 10 kHz. Considering these overlapping frequency ranges, there is a high potential for anthropogenic noise to mask marine mammal communication (Richardson et al. 1998; Lesage et al. 1999; Sousa-Lima and Clark 2008; Van Parijs et al. 2009). The cause of elevated sound levels from September to December and a subsequent decrease from January to March at both sites is suspected to be due a combination of marine mammal migration in the winter (Gregr et al. 2000) that, in turn, largely reduced sound production from January to April; seasonal shipping patterns that resulted in a decrease in vessel noise after December (C. Pomerleau, personal communication);

and seasonal wind patterns and storms (e.g., Wenz 1962) that can contribute to the marine soundscape specifically in the winter.

Although ocean observatories such as NEPTUNE Canada provide excellent opportunities to conduct long-term acoustic research, there are limitations. Most important is self-generated noise. Active sonar and moving equipment as well as regular maintenance efforts can contribute largely to ambient-noise levels and thereby complicate the results of the above analysis (Wall et al. 2014). In 2012, efforts were made to improve the Folger Passage Deep passive acoustic data quality by moving the hydrophone further from the node, thereby reducing noise from the echo sounder. Further analyses comparing the improved (noise-reduced and new calibrated hydrophone) acoustic data currently being collected at this node as well as additional efforts to reduce instrument noise at the Barkley Canyon Axis node are recommended to be able to provide more accurate and longer term noise estimates.

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Chapter 152
Behavioral Response of Reef Fish and Green Sea Turtles to Midfrequency Sonar

Stephanie L. Watwood, Joseph D. Iafrate, Eric A. Reyier, and William E. Redfoot

Abstract There is growing concern over the potential effects of high-intensity sonar on wild fish populations and commercial fisheries. Acoustic telemetry was employed to measure the movements of free-ranging reef fish and sea turtles in Port Canaveral, FL, in response to routine submarine sonar testing. Twenty-five sheepshead (*Archosargus probatocephalus*), 28 gray snapper (*Lutjanus griseus*), and 29 green sea turtles (*Chelonia mydas*) were tagged, with movements monitored for a period of up to 4 months using an array of passive acoustic receivers. Baseline residency was examined for fish and sea turtles before, during, and after the test event. No mortality of tagged fish or sea turtles was evident from the sonar test event. There was a significant increase in the daily residency index for both sheepshead and gray snapper at the testing wharf subsequent to the event. No broad-scale movement from the study site was observed during or immediately after the test.

Keywords Anthropogenic noise • Fish • Sea turtles • Sonar • Telemetry • Tagging

1 Introduction

Midfrequency sonar has been demonstrated to induce behavioral responses in marine mammals (Tyack et al. 2011; DeRuiter et al. 2013); however, the effect of sonar on other marine species is not well understood. Although it has been

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suggested that high-intensity midfrequency sonar is potentially capable of injury or mortality in fish species that are very close to the source, neither has been demonstrated in a field setting (Jørgensen et al. 2005; Popper 2008), and behavioral studies examining the effects of midfrequency sonar on unrestrained fish in their natural habitat are limited (Popper 2008; Slabbekoorn et al. 2010; Normandeau Associates, Inc. 2012). The most prominent studies thus far were conducted in enclosed, restrained environments from which behavior cannot be extrapolated to wild animals (Schwarz and Greer 1984; Jørgensen et al. 2005; Popper et al. 2007), have only investigated the immediate behavioral responses of a single species (Knudsen et al. 1992, 1994; Gearin et al. 2000), or did not include direct behavioral observations or assess long-term survival (Culik et al. 2001).

There are also very limited studies of sea turtle behavioral response to high-intensity sounds, with most efforts focused on measuring avoidance or changes in swimming activity in response to air gun sounds (O'Hara and Wilcox 1990; Moein et al. 1994; McCauley et al. 2000; Weir 2007). Although the range of turtle hearing is likely limited to an upper level of 2 kHz, to date there have been no behavioral response studies of turtles to midfrequency sonar.

The main objective of this study was to use fine-scale acoustic telemetry to assess the residency of fish and sea turtles before, during, and after a routine submarine sonar test event. Sheepshead (*Archosargus probatocephalus*) and gray snapper (*Lutjanus griseus*) were chosen as target fish species due to known site fidelity to hard-bottom habitats in the study area (Reyier et al. 2010), hearing ranges and sensitivities that are characteristic of fish without highly derived hearing specializations (Popper 2008), and the widespread occurrence of the Sparidae and Lutjanidae families in subtropical and tropical coastal marine waters throughout the world. The green sea turtle (*Chelonia mydas*) was also a target species because it possesses similar auditory structures and presumed hearing capabilities as the six sea turtle species that comprise the family Cheloniidae, and a previous mark-recapture study has indicated the importance of the Cape Canaveral region as a foraging and resting area for juveniles (Ehrhart et al. 2007).

2 Methods

2.1 Study Area

Port Canaveral is a man-made multiuse harbor on the central east coast of Florida that supports cruise ship terminals, recreational and commercial fishing interests, and military testing and training activities. The wharf structures within the Port create valuable habitats that have resulted in robust resident populations of tropical reef fish species (Reyier et al. 2010). A significant portion of the daily feeding and resting activity of the target species is centralized on the wharf, rock revetments, and associated floating dock spaces. Although fish and turtles are exposed to low levels of anthropogenic noise regularly from the activity at Port Canaveral, pier-side testing of navy sonar systems occurs on an intermittent basis and typically for short durations.

The sonar test examined in this study occurred at the northern end of Trident Wharf over a 2-day period in June 2012. The sonar signals, duty cycle, and source levels followed a typical protocol for a pier-side submarine sonar test event.

2.2 Acoustic Telemetry Arrays

Two array configurations were utilized in this study to collect data at different temporal and spatial scales. Vemco VR2W (AMIRIX Systems, Inc.) autonomous telemetry receivers were deployed in the West, Middle, and Trident Basins to provide broad-scale coverage within the Port Canaveral area (Fig. 152.1).

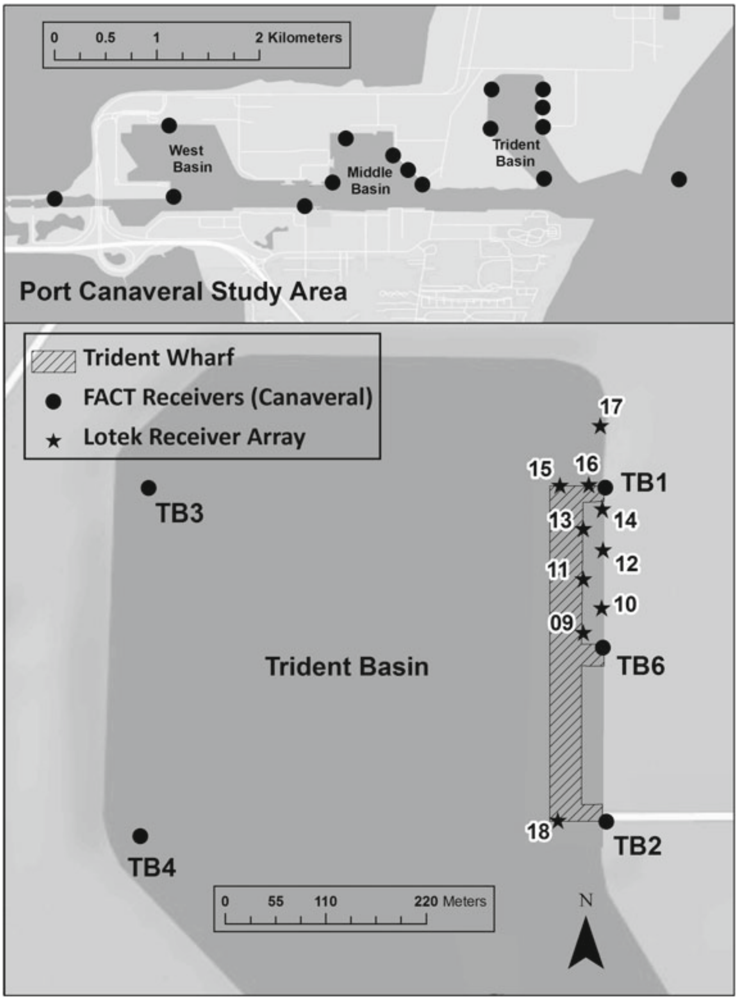

Fig. 152.1 Vemco and Lotek receiver arrays within Port Canaveral. FACT, Florida Atlantic coast telemetry

Regional tracking for those tagged fish that emigrated out of the Port Canaveral study area was accomplished via the Florida Atlantic coast telemetry (FACT) array, which at the time consisted of 200 acoustic receivers deployed across a 300-km section of the east Florida coastline. Vemco receivers within the immediate Canaveral Harbor study area were bottom mounted and secured via a guy anchor.

Lotek WHS3250 receivers (Lotek Wireless, Inc.) comprised the second fine-scale array and were secured via a guy anchor or bracket mounted directly offset from pilings on the interior of Trident Wharf in the Trident Basin only. Receivers mounted on wharf pilings were outfitted with acoustic scatterboards to help minimize acoustic reflection and localization errors. These custom-built boards were composed of closed cell foam and plywood mounted directly to pilings supporting a receiver.

2.3 Collection and Tagging

Lotek multimode transmitters (MM-MR-8-SO-TP) were used to gather movement data for both fish species and a subset of the turtles. These transmitters emit two discrete coded signals that are separately compatible with existing Vemco and Lotek receivers. The expected battery life for the transmitters ranged from 73 to 163 days depending on the pulse interval of signal emissions. Seventeen of the turtles were tagged with Vemco V9P-2L tags, which are only compatible with Vemco receivers.

A total of 25 sheepshead and 28 gray snapper were captured either by gill net or hook-line angling 1 week before the test event. Target fish had a minimum weight of 300 g in air to ensure that the tag accounted for no more than 2% of body weight (Winter 1983). Fish were anesthetized in a solution of 75 mg/L of tricaine methanosulfonate (MS-222, Western Chemical, Inc.) in seawater in a 10-gal holding tank. The fish were then placed ventral side up for surgical implantation of acoustic transmitters while the gills were irrigated with fresh seawater. The incisions were closed with two absorbable sutures followed by application of tissue adhesive and triple antibiotic ointment. Standard length, weight, method of capture, and release condition were recorded for all fish. Each fish was fitted with a small external dart tag (Hallprinta) in case of angler recapture. The fish were allowed to fully recover in aerated seawater for a minimum of 10 min and were observed swimming normally before release.

Twenty-nine green sea turtles were captured using tangle nets or dip nets. The tangle nets consisted of multifilament nylon twine mesh hung from a braided polypropylene top line and a braided polypropylene continuous lead-core bottom line. The turtles were also opportunistically captured with long-handled, large-hoop dip nets. After transport to the shore, standard morphometric measurements were recorded and the turtle was tagged externally using inconel alloy flipper tags and a passive internal transponder (PIT) tag (Destron-Fearing) inserted subcutaneously in the right front flipper proximal to the wrist joint. The Vemco or Lotek acoustic transmitters were attached externally with two-part marine epoxy to the 3rd and 4th right or left costal scutes depending on the condition of the scutes. Once the epoxy hardened, the turtle was released back into the basin.

2.4 Residency

Raw detection data from each receiver were filtered to minimize the probability of accepting false-positive detections (Pincock 2008). Residency indexes (RIs) were calculated on a daily basis for all fish to represent the proportion of a given time window that an individual was detected on the Trident Wharf Vemco receivers (TB1, TB2, and TB6). RIs were also calculated for combined detections on all three wharf receivers (a fish was considered present if it was detected on any of the three wharf receivers) to examine broader scale residency at the wharf. Before, during, and after sonar test time windows utilized in comparisons were structured by days 1–7, 8–9, and 10–16 posttagging, respectively. The Wilcoxon matched-pairs signed-rank test was used to test for significant differences between the pretest and posttest time windows at $\alpha \leq 0.05$.

RIs were also calculated for Lotek receivers along the Trident Wharf for fish only. Before, during, and after sonar test periods were structured in 36-h continuous-time windows. For this comparison, detections were combined into three receiver zones representing subsections of the wharf habitat. Receiver (REC) zones 1, 2, and 3 were composed of REC09/10/11, REC12/13/14, and REC15/16/17, respectively. Tests for significance between groups were conducted utilizing a nonparametric repeated-measures one-way ANOVA. Post hoc tests for significance between paired groups (before to during, during to after, and before to after) were conducted utilizing Wilcoxon matched-pairs signed-rank test. Significant differences were considered at $\alpha \leq 0.017$ after a Bonferroni correction for multiple comparisons.

3 Results

Fish and turtle data were monitored on the Canaveral Vemco and FACT arrays for 125 days after release of the animals. The tagged fish were detected on Vemco receivers for a median of 88 days (range 5–125 days, mode 125 days), while turtles were detected on Vemco receivers for a median of 63 days (range 6–125 days, mode 115 days). Figure 152.2 shows the number of detections of each species on Trident Wharf for the first 60 days after the start of tagging.

Table 152.1 shows a summary of the mean ± SE values for the RI on Trident Wharf. For sheepshead, there was a significant increase in the RI at TB6 ($z = -2.06$, $n = 25$, $P = 0.04$) and at the Trident Wharf receivers combined ($z = -2.36$, $n = 25$, $P = 0.02$) after the test event. Gray snapper showed a significant decrease in residency at TB2 posttest ($z = -2.50$, $n = 28$, $P = 0.013$), although there was a significant increase at the Trident Wharf receivers combined ($z = -2.01$, $n = 287$, $P = 0.045$). Green sea turtles overall had lower RI values on the wharf and also showed a significant decrease in residency at TB2 only ($z = -2.72$, $n = 29$, $P = 0.007$).

In the short term, significant differences between time periods were reported for the hourly RI for sheepshead at REC09/10/11 ($H = 10.71$, df $= 2$, $P = 0.005$) and for

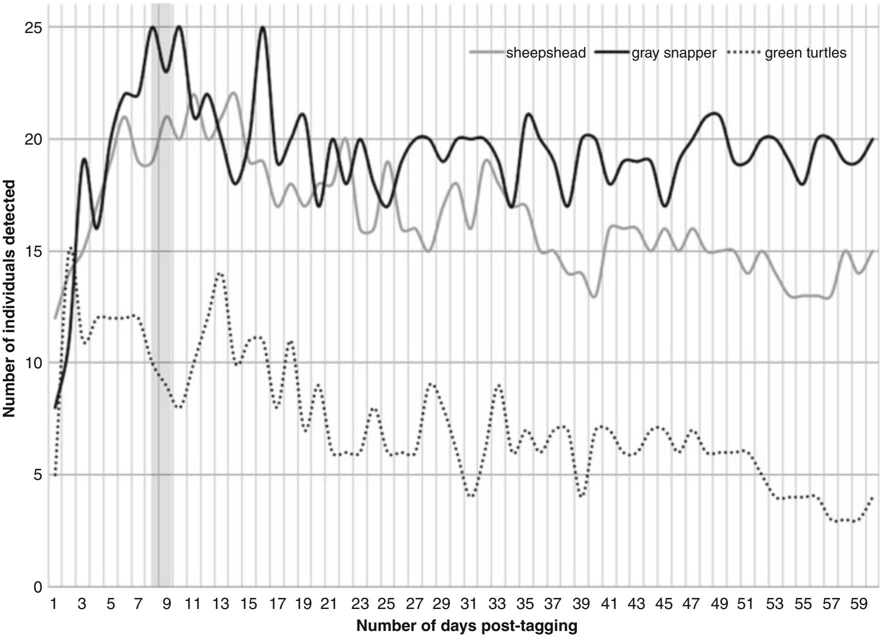

Fig. 152.2 Daily detections of sheepshead, gray snapper, and green sea turtles at Trident Wharf Vemco receivers (TB1, TB2, and TB6). *Gray area* is the sonar test period (days 8–9)

Table 152.1 Daily residency index for sheepshead, gray snapper, and green sea turtles before, during, and after the sonar test

	Sheepshead	Gray snapper	Sea turtle
TB1 receiver			
Before	0.35 ± 0.07	0.44 ± 0.06	0.07 ± 0.03
During	0.36 ± 0.09	0.57 ± 0.09	0.05 ± 0.04
After	0.36 ± 0.09	0.46 ± 0.07	0.08 ± 0.03
TB2 receiver			
Before	0.09 ± 0.03	0.20 ± 0.04	0.26 ± 0.05
During	0.12 ± 0.06	0.27 ± 0.08	0.16 ± 0.05
After	0.12 ± 0.05	0.32 ± 0.08	0.13 ± 0.05
TB6 receiver			
Before	0.43 ± 0.07	0.09 ± 0.03	0.22 ± 0.06
During	0.52 ± 0.09	0.09 ± 0.04	0.24 ± 0.08
After	0.57 ± 0.09	0.12 ± 0.04	0.26 ± 0.07
Trident Wharf			
Before	0.67 ± 0.06	0.60 ± 0.04	0.39 ± 0.06
During	0.80 ± 0.07	0.86 ± 0.05	0.33 ± 0.08
After	0.82 ± 0.05	0.77 ± 0.05	0.37 ± 0.08

Values are means ± SE. Before, days 1–7; during, days 8–9; after, days 10–16

Table 152.2 Hourly residency index for sheepshead and gray snapper for 36-h windows before, during, and after the sonar test

	Sheepshead	Gray snapper
REC09/10/11		
Before	0.68 ± 0.08	0.43 ± 0.06
During	0.61 ± 0.08	0.36 ± 0.06
After	0.65 ± 0.08	0.39 ± 0.06
REC12/13/14		
Before	0.78 ± 0.06	0.57 ± 0.08
During	0.75 ± 0.06	0.50 ± 0.06
After	0.81 ± 0.06	0.47 ± 0.06
REC15/16/17		
Before	0.61 ± 0.07	0.62 ± 0.08
During	0.61 ± 0.07	0.58 ± 0.06
After	0.67 ± 0.06	0.55 ± 0.06
Trident Wharf		
Before	0.74 ± 0.06	0.55 ± 0.08
During	0.78 ± 0.06	0.49 ± 0.07
After	0.79 ± 0.05	0.46 ± 0.07

Values are means ± SE. Before, days 6.5–8; during, days 8.5–9; after, days 9.5–11

gray snapper at all Lotek receivers combined ($H = 6.46$, df = 2, $P = 0.040$). Post hoc comparisons showed a significant decrease in hourly residency for sheepshead at REC09/10/11 for the before test compared with the during test time period ($z = -3.15$, $n = 25$, $P = 0.002$). Post hoc comparisons for gray snapper were not significant. A summary of mean ± SE values for the hourly RIs in the Trident Basin are presented in Table 152.2.

4 Discussion

Sheepshead and gray snapper exposed to a typical pier-side submarine sonar test event showed some short-term declines in residency near particular individual receivers during and after the test, but no long term displacement from the wharf habitat overall was observed for any species. Sonar testing is infrequent in the Trident Basin, especially within the short-term residence time of 2–4 weeks typical of these species. Although the sonar signals may represent a novel stimulus, Port Canaveral is a very urban environment, and marine species here may be habituated to higher levels of anthropogenic sound, including vessel and construction noise. These individuals could therefore be less likely to respond than naïve populations. Nevertheless, the sheepshead, gray snapper, and green sea turtles present in the Trident Basin did not demonstrate significant displacement in response to a typical pier-side submarine sonar test event.

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Chapter 153
Underwater Equal-Latency Contours of a Harbor Porpoise (*Phocoena phocoena*) for Tonal Signals Between 0.5 and 125 kHz

Paul J. Wensveen, Léonie A.E. Huijser, Lean Hoek, and Ronald A. Kastelein

Abstract Loudness perception can be studied based on the assumption that sounds of equal loudness elicit equal reaction time (RT; or "response latency"). We measured the underwater RTs of a harbor porpoise to narrowband frequency-modulated sounds and constructed six equal-latency contours. The contours paralleled the audiogram at low sensation levels (high RTs). At high-sensation levels, contours flattened between 0.5 and 31.5 kHz but dropped substantially (RTs shortened) beyond those frequencies. This study suggests that equal-latency-based frequency weighting can emulate noise perception in porpoises for low and middle frequencies but that the RT-loudness correlation is relatively weak for very high frequencies.

Keywords Auditory weighting • Loudness • Noise effects • Odontocetes • Reaction time

1 Introduction

Noise exposure regulations for the protection of marine mammals generally include acoustic risk thresholds that are expressed as a sound level that is weighted by the frequency response of the hearing system of a species or species group. Such weightings greatly simplify noise regulations because they result in single weighted thresholds that apply to many sounds irrespective of their frequency spectra. Three types of weighting for marine mammals are currently available: (1) audiogram-based

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methods (e.g., Verboom and Kastelein 2005); (2) “M-weighting,” a method based on the frequency bandwidth of hearing (Southall et al. 2007); and (3) weighting functions that are derived from equal-loudness contours (Finneran and Schlundt 2011). The latter probably emulates the auditory response most accurately for mid- and high-intensity sounds; however, equal-loudness data currently exist only for the bottlenose dolphin (*Tursiops truncatus*) and due to the difficulty of training marine mammals to participate in loudness comparison tests, it is unlikely that many other species will be tested in the near future.

A possible alternative is frequency weighting based on reaction time (RT; or “response latency,” defined as the time elapsing between the onset of a stimulus and the onset of the subject’s response) of the animal to sound. In humans, a relationship between RT and perceived loudness has been determined using a variety of psychophysical methods (Marks and Florentine 2011). Equal-latency contours, which describe the relationships between unweighted sound pressure level (SPL), frequency, and RT, are similar in shape to equal-loudness contours in humans (Marshall and Brandt 1980), and equal-latency contours of animals are similar to their expected equal-loudness counterparts (Kastelein et al. 2011). Hence, frequency weighting based on equal latency may be a relatively efficient method to improve noise exposure regulations for marine mammals. In this study, we measured the equal-latency contours of a harbor porpoise (*Phocoena phocoena*) for a wide range of frequencies and sound levels to assess whether weightings can be derived from such contours in the future.

2 Materials and Methods

Research sessions were conducted at the Sea Mammal Research Company (SEAMARCO) Research Institute, The Netherlands, in an indoor test pool under low background noise conditions. The test subject was a 6–7-year-old male harbor porpoise that had previously participated in a number of psychoacoustic studies. More details about the subject animal and test facility are described by Kastelein et al. (2012).

The sound signals were narrowband frequency-modulated signals with center frequencies of 0.5, 1, 2, 4, 16, 31.5, 63, 80, and 125 kHz. Received SPLs ranged from 59 to 168 dB re 1 μPa (depending on the frequency), and test levels were spaced 10 dB apart. The sound production equipment consisted of a laptop computer, a 16-bit data-acquisition device, a custom-built attenuator, a high-power amplifier, and four underwater projectors. The output of the sound system and the background noise conditions were checked at the start of each research session. The equipment used to measure the SPL of the test signals and background noise consisted of a laptop computer, a spectrum analyzer, and two calibrated hydrophones. The SPL at the locations of the auditory meatus of the porpoise differed by 0–7 dB (mean absolute difference was 3 dB) and the difference in mean SPL between measurement days was 1–3 dB (depending on the frequency).

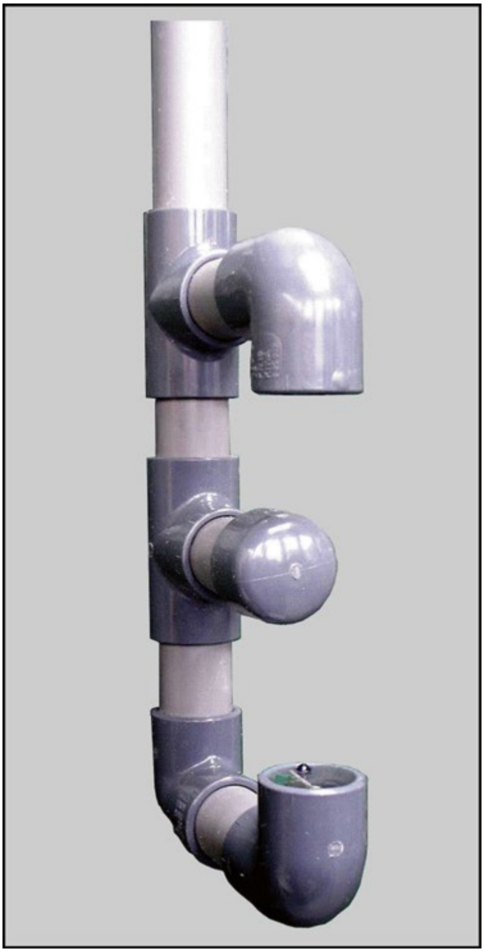

Fig. 153.1 The underwater listening station of the porpoise. The infrared light detector and emitter that were used to measure the auditory reaction times (RTs) of the animal were embedded in epoxy in the top and bottom bracket, respectively

Research sessions consisted of 30–35 trials and lasted for ~20 min. The experimental protocol was similar to that of Kastelein et al. (2010), with the main difference being a higher proportion of signal-present trials. Within-session signal levels were randomized, with the restriction that the level difference between successive trials was not more than 30 dB (Wagner et al. 2004). Only one frequency was tested per session. During research trials, the porpoise was positioned at a water-filled PVC listening station 1 m below the water surface. The RTs of the porpoise were measured using an infrared light sensor that was incorporated into the listening station (Fig. 153.1).

A power law was fitted to the median RT-level datasets for each frequency

$$\mathrm{RT} = \beta\left(\mathrm{I}/\mathrm{I}_0\right)^{-\alpha} \tag{153.1}$$

where I/I_0 is the ratio of the intensity of the test stimulus (I) to the intensity of a stimulus at threshold (I_0), exponent α is the slope on a log-log scale, and β is the y-intercept (equal to the RT at sensation level = 0 dB). One or two median RTs to signals at sensation levels <30 dB were omitted when this substantially improved the r^2. The best-fitting functions were evaluated at the contour reference values of 150, 160, 170, 180, 190, and 200 ms to obtain the SPL data for the equal-latency contours.

3 Results

The median RTs of the porpoise were inversely related to the SPL of the sound signals at each test frequency. The fits of the auditory RT functions (Eq. 153.1) to the median RTs were satisfactory (r^2: 0.90–0.99). The 190- and 200-ms equal-latency contours roughly paralleled the animal's hearing threshold and included the notch at 63 kHz (Fig. 153.2). The mean difference between the SPL of the hearing threshold and the 200-ms contour was 31 dB. The average spacing between adjacent equal-latency contours was greater in the midrange (16–31.5 kHz; 11–13 dB) than in the low-frequency (0.5–4 kHz; 6–9 dB) and especially high-frequency (63–125 kHz; 5–8 dB) range. As a result, the 150–180-ms equal-latency contours were flatter (less variation in SPL with frequency) between 0.5 and 31.5 kHz but dropped substantially (RTs shortened) beyond those frequencies.

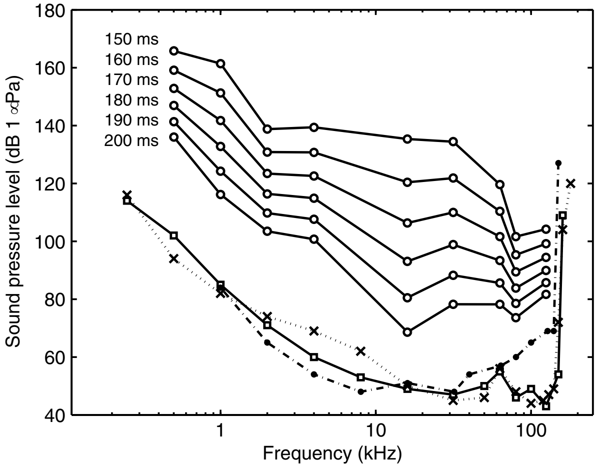

Fig. 153.2 The 150–200 ms equal-latency contours of the harbor porpoise (*solid lines with circles*) plotted in combination with the audiogram of the subject measured 2–3 years earlier (*solid line with squares*, Kastelein et al. 2010) and the audiograms of two other harbor porpoises (*dotted line with crosses*, Andersen 1970; *dashed-dotted line with circles*, Kastelein et al. 2002, 2010)

4 Discussion

Various studies have shown that RT correlates with loudness (Marks and Florentine 2011), but very little information exists about this correlation for ultrasonic sounds that can be heard by odontocetes. For low-sensation levels, the equal-latency contours of the harbor porpoise are similar in shape to expected equal-loudness contours. For high-sensation levels, the contours are also similar at frequencies up to 31.5 kHz. However, the animal responded relatively rapidly to signals of very high frequencies; therefore, the contours decreased and diverged from the expected equal-loudness contours. It seems unlikely that these relatively short RTs resulted from increases in perceived loudness because the dynamic hearing range of the harbor porpoise should be relatively large at these frequencies where echolocation click energy is centered.

As often seen in psychoacoustic studies with captive marine mammals, the sample size was low ($n = 1$), and it is therefore not known whether the equal-latency contours of comparable conspecifics (young adult, male, normal hearing) are similar to those reported here. However, the behavioral audiogram of the study animal collected 2–3 years earlier by Kastelein et al. (2010) was very similar to those of two other harbor porpoises (Andersen 1970; Kastelein et al. 2002, 2010), and the equal-latency contours measured here roughly followed the shape of all the audiograms (Fig. 153.2). Auditory weighting based on RT may therefore be a feasible method for low and middle frequencies when direct measures of loudness are unavailable. This method would result in more realistic weighted sound levels and could therefore improve the predictability of the behavioral and physiological effects of noise on marine mammals in cases where these effects correlate well with the perceived loudness of the noise.

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Chapter 154
Underwater Hearing in Turtles

Katie L. Willis

Abstract The hearing of turtles is poorly understood compared with the other reptiles. Although the mechanism of transduction of sound into a neural signal via hair cells has been described in detail, the rest of the auditory system is largely a black box. What is known is that turtles have higher hearing thresholds than other reptiles, with best frequencies around 500 Hz. They also have lower underwater hearing thresholds than those in air, owing to resonance of the middle ear cavity. Further studies demonstrated that all families of turtles and tortoises share a common middle ear cavity morphology, with scaling best suited to underwater hearing. This supports an aquatic origin of the group. Because turtles hear best under water, it is important to examine their vulnerability to anthropogenic noise. However, the lack of basic data makes such experiments difficult because only a few species of turtles have published audiograms. There are also almost no behavioral data available (understandable due to training difficulties). Finally, few studies show what kinds of sounds are behaviorally relevant. One notable paper revealed that the Australian snake-necked turtle (*Chelodina oblonga*) has a vocal repertoire in air, at the interface, and under water. Findings like these suggest that there is more to the turtle aquatic auditory scene than previously thought.

Keywords Middle ear • Auditory • Reptile • Amphibious

1 Introduction

Turtles and tortoises (testudines) were historically considered the least vocally active group of extant reptiles (Gans and Maderson 1973). The testudine hearing range is confined to low frequencies (mostly under 1 kHz), and they have higher auditory thresholds than other reptiles. Furthermore, work with amphibious and aquatic turtles has been hindered by technical difficulties in executing experiments with low-frequency sounds underwater. Finally, testudines are difficult to train for a

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variety of reasons, particularly motivation (Patterson 1966). Nevertheless, understanding testudine hearing has become increasingly important. Many aquatic testudines are endangered, including six of seven total sea turtle species (International Union for Conservation of Nature 2013). These animals encounter anthropogenic noise in a variety of places of ecological importance: along their migration routes, near mating and nesting sites, and in their year-round habitats. The behavioral and physiological effects of this noise are not understood.

2 Ecological Relevance of Acoustic Stimuli

Vocalizations for many species are limited to grunting, generally associated with mating (Campbell and Evans 1967, 1972). It has been calculated that for species with described courtship behavior, 35% have vocalization associated with mounting (Galeotti et al. 2005). For example, Hermann's tortoises (*Testudo hermanni*) vocalize in association with mating, specifically mounting. Females exhibit preference for higher frequency, short-duration, high-rate vocalizations from the males in playback experiments (Galeotti et al. 2004). In this case, higher frequency calls are around 750 Hz and lower frequency calls are around 500 Hz. Some turtles, however, may be more vocal than previously thought. Giles et al. (2009) documented the vocal repertoire of the snake-necked turtle (*Chelodina oblonga*), a river turtle found in Australia. This species not only generates multiple calls in air, underwater, and at the interface and even vocalizes in chorus. Similarly, the giant South American turtle (*Podocnemis expansa*) also vocalizes in air, underwater, and in ovo (Ferrara et al. 2013). These calls were categorized into 11 types. Females were observed approaching the vocalizations of hatchlings, and embryonic turtles began vocalizing 8–36 h before hatching. The authors hypothesize that these calls could have multiple functions, including parental care, synchronization of hatching, and migratory group cohesion.

The findings reviewed above suggest that further investigation of many other species is warranted because they provide strong evidence for the ecological relevance of auditory cues to testudines. Little information is available about the vocalizations of sea turtles. Anecdotally, while using underwater television, Kumpf (1964) observed roaring noises when sea turtles were seen on the screen. Grunts and similar vocalizations have been documented in association with pain, mating, and nesting (Carr 1969; Campbell and Evans 1972; Mrosovsky 1972; Cook and Forrest 2005). Spectrograms of these vocalizations have their highest energy between 300 and 500 Hz (Mrosovsky 1972), which is consistent with the best hearing frequencies for sea turtles (Ridgway et al. 1969). The communication function, if any exists, of these vocalizations is unknown.

Conspecific vocalizations are not the only relevant stimuli in the auditory scene (for a recent review of problems and progress in auditory scene analysis, see Shamma and Micheyl 2010). Acoustic stimuli from predators and prey as well as environmental acoustic cues may also be relevant. The lack of information about what stimuli comprise the testudine acoustic scene impedes understanding of their behavior as well as the effects of changes in the auditory scene as a result of human activity. Finally, these findings have not been followed up with auditory threshold measurements, closer examination of the ecological relevance of the calls, or investigations of closely related species vocalizations.

3 Auditory Anatomy

The sound receiving structure of the turtle ear is a cartilaginous tympanic disk overlaid with a thin layer of relatively undifferentiated skin, without an external ear (Wever 1978; Christensen-Dalsgaard et al. 2012; Fig. 154.1). The extracolumella connects the interior of the tympanic disk to the columella, the single ossicle (Fig. 154.1). The columella runs through the middle ear cavity and terminates in the columellar footplate, which transfers the mechanical energy of the sound to the inner ear. The motion of the fluid in the inner ear displaces the hair cells, resulting in stimulation of the auditory nerve.

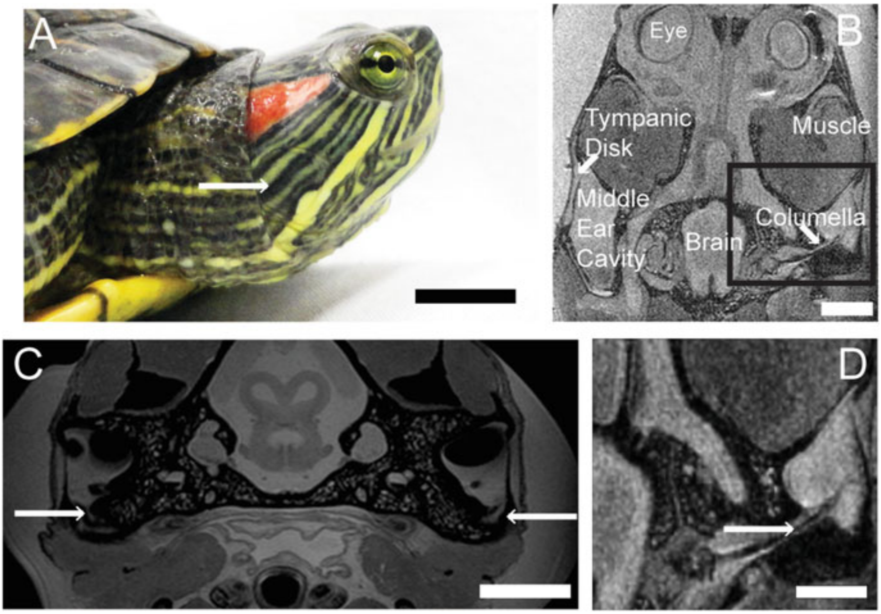

Fig. 154.1 Anatomy of auditory system of a *red-eared* slider. (**a**) *Lateral* view of head of adult female *red-eared* slider (scale bar 1 cm). *Arrow* indicates relatively undifferentiated skin overlaying the tympanic disk. (**b**) *Horizontal* magnetic resonance image (MRI; scale bar 500 mm) (**c**) *Transverse* view MRI at the level of the tectum. *Arrows* indicates Eustachian tubes (scale bar 500 mm). Area labeled "Muscle" is the splenius capitus. (**d**) *Horizontal* view MRI enlarged from *box* in (**b**). The columella connects the tympanic disk to the inner ear. *Arrow* indicates the columella (scale bar 500 mm). From Willis et al. (2013). Used under Creative Commons Attribution License

Sea turtles have a slightly different auditory periphery than other testudines. Fatty connective tissue is attached to the interior side of the tympanic disk (Ridgway et al. 1969). The columella runs from the tympanic disk though connective tissue to terminate on the columellar footplate. There are some hypotheses about the function of this tissue, including that it is an adaptation to deep diving (Ridgway et al. 1969) and that it is analogous to the fat channels in the lower jaw of some marine mammals (Ketten et al. 1999). Any hypotheses are complicated by the high variation in fatty tissue volume across species, within a single species, and bilaterally within the same animal. To date, there are no published studies systematically analyzing this tissue. Neither the biochemical nor the acoustic properties have been investigated. Although it is difficult to obtain tissue from these protected species, these experiments are vital to determining the function, if any, of the fatty connective tissue in sea turtle ears.

4 Hearing in Air and Water

Because of the physics of sound transmission, an ear that is highly effective in air will not be effective under water and vice versa. Therefore, the ears of amphibious animals, like many testudines, evolve under constrained optimization. Turtle ears transmit sound both in air and under water (Christensen-Dalsgaard et al. 2012) but are less sensitive to airborne sound than other reptiles (Wever 1978). Their hearing thresholds have been measured both in air and under water using auditory evoked potentials (AEPs; Christensen-Dalsgaard et al. 2012). AEPs are less sensitive than behavioral tests but are a good indicator of the range of acoustic stimuli an animal can hear as well as the stimuli to which it is most sensitive. Recently, Martin et al. (2012) demonstrated that a behavioral audiogram and an AEP audiogram of one loggerhead turtle (*Caretta caretta*) were similar to each other. AEP experiments have revealed that testudines generally hear below 1,000 Hz, with best frequencies ranging from 300 to 600 Hz depending on the species.

The red-eared slider (*Trachemys scripta elegans*), an amphibious pond turtle, is commonly used species in biological experiments because it is a destructive invasive species in many places. The red-eared slider has a lowest hearing threshold of 60-dB sound pressure level (SPL) at 400–500 Hz in air, and underwater AEPs showed the lowest threshold to be 80 dB re 1 μPa at best frequency (400–500 Hz; Christensen-Dalsgaard et al. 2012). In this study, direct vibration of the tympanic disk also revealed lowest displacement thresholds at 500 Hz. The efficacy of the ear depends on the sound-transmitting medium. Because animal tissue has approximately the same impedance to sound as to water, most of the body is essentially transparent to underwater sound. The air that fills the turtle middle ear vibrates in the underwater sound field and thus vibrates the tympanum and transfers sound energy to the inner ear (Christensen-Dalsgaard et al. 2012; Willis et al. 2013). The air-filled turtle middle ear is thus analogous to the swim bladders coupled to the ear of otophysine fish (Popper and Fay 2011). Depending on the volume and structure of the middle ear, additional auditory sensitivity can be conferred by sound resonating inside the middle ear cavity, and AEP and laser vibrometry results indicate that the turtle ear transmits sound more efficiently under water than in air (Christensen-Dalsgaard et al. 2012).

5 Cross-Species Analysis of Hearing

To understand how the testudine ear may have evolved, Willis et al. (2013) measured the volume and described the morphology of the middle ear cavities of representative species from all but one extant family of testudines. This study showed mathematically that the volume of the air-filled middle ear cavities of all included species is such that the cavity would resonate in an underwater sound field within the animals' hearing range (under 1 kHz). In air, the middle ear cavities would resonate far outside the animals' hearing range (about 6 KHz; Wever and Vernon 1956). These findings emphasize the conclusion from Christensen-Dalsgaard et al. (2012) that improved hearing under water is conferred by large middle ear cavities. Large middle ear cavities in all extant taxa of testudines suggest that the most recent common ancestor of extant testudines was aquatic (likely secondarily aquatic).

Given this information, turtle hearing should be considered in studies of the effects of underwater anthropogenic noise. Although in-air audiograms are not available for many species, only two species, the red-eared slider (Christensen-Dalsgaard et al. 2012) and the loggerhead turtle (Martin et al. 2012), have underwater audiograms that have been published. Therefore, it is not only unknown what turtles are listening to underwater but also what they would even be able to hear.

6 Behavioral and Physical Effects

Behavior in response to acoustic stimuli is not well documented in testudines. In a playback study of diamondback terrapins (*Malaclemys terrapin terrapin*) using boat noise, some animals were observed to increase or decrease swimming speed while others did not alter their behavior at all (Lester et al. 2012). Some members of an aggregate of loggerhead turtles were observed to dive in what appeared to be a response to the firing of air guns (DeRuiter and Larbi Doukara 2012). General avoidance of air gun noise by loggerhead turtles has also been documented, but this avoidance is not robust (O'Hara and Wilcox 1990). In response to vibration on the shell (another probable conductor of sound), multiple species of testudines have been shown to exhibit a head-withdraw reflex, which is a general startle reflex in testudines (Lendhardt 1982). Understanding physiological effects of noise exposure cannot usually be done in a systematic laboratory setting because many turtle species are endangered to some degree. Assessing damage to a noise exposure from an anthropogenic source in the animals' natural environment would be difficult, but not impossible, to analyze and interpret. Options for addressing this problem include using common, invasive species (e.g., red-eared slider) for controlled experiments, rigorous monitoring of noise exposure over an animal's lifespan, and careful necropsy after natural death focusing on auditory structures. Utilizing multiple complementary techniques will enable substantial progress in the field of turtle hearing.

7 Conclusions

The primary problem with understanding the effects of aquatic anthropogenic noise on testudines is the information gap in the basics of testudine hearing. Because testudines hear better in water than in air, more consideration should be given to the possible effects of aquatic noise on this group. Specific data that the scientific community needs to move forward include audiograms from more species, descriptions of the communication functions of vocalizations, and rigorously documentation of the behavioral and physiological effects of noise exposure.

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Chapter 155
Quantitative Measures of Anthropogenic Noise on Harbor Porpoises: Testing the Reliability of Acoustic Tag Recordings

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Abstract In recent years, several sound and movement recording tags have been developed to sample the acoustic field experienced by cetaceans and their reactions to it. However, little is known about how tag placement and an animal's orientation in the sound field affect the reliability of on-animal recordings as proxies for actual exposure. Here, we quantify sound exposure levels recorded with a DTAG-3 tag on a captive harbor porpoise exposed to vessel noise in a controlled acoustic environment. Results show that flow noise is limiting onboard noise recordings, whereas no evidence of body shading has been found for frequencies of 2–20 kHz.

Keywords Vessel • Calibration • DTAG-3 • Flow noise

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1 Introduction

Evaluation of the effects of anthropogenic sounds on *Phocoena phocoena* (harbor porpoise) is primarily based on presence-absence studies before, during, and after transient anthropogenic activities. Little is known about what individual animals are exposed to on a daily basis and how they react to specific noise sources. A recent study on broadband vessel noise in Danish waters has found that noise from a diverse range of ship types substantially elevates ambient-noise levels over a broad frequency from 0.025 to 160 kHz (Hermannsen et al. 2014). The authors estimated that the signal-to-noise ratio for porpoises within 490 m from a vessel could be reduced by 30 dB in the 1/3-octave level around 125 kHz. Vessel noise may thus induce severe masking on harbor porpoises. These high-frequency specialists (Kastelein et al. 2010) have recently been shown to also react to medium- to high-frequency components of vessel noise, with no signs of habituation despite years of exposure during captive life in a harbor (Dyndo 2013). Thus, porpoises inhabiting the heavily ship-trafficked shallow waters are likely frequently exposed to medium-to high-frequency vessel noise to which they may show adverse behavioral reactions, but direct measurements are lacking.

Over the last decade, a number of sound and movement recording tags have been deployed to sample the acoustic field experienced by cetaceans and their reactions to it (e.g., Aguilar de Soto et al. 2006; Madsen et al. 2006; DeRuiter et al. 2013; Goldbogen et al. 2013). Latest advances in battery and memory storage technologies have allowed for higher sampling rates and a decrease in tag size, making the DTAG-3 suitable for small cetacean species such as the harbor porpoise. However, little is known about how tag placement and an animal's speed and orientation in the sound field affect the reliability of on-animal audio recordings as proxies for actual exposure. Due to the short wavelengths, high frequencies are particularly prone to be affected by body shading and may be underestimated in tag recordings from animals even as small as the harbor porpoise. Flow noise may, in turn, lead to an overestimation of low-frequency noise impacts. The objective of this study was therefore to uncover the relationship between the actual exposure and the tag-recorded vessel noise levels from harbor porpoises in a controlled acoustic environment.

2 Methods

Measurements were conducted in an 8- × 13-m net pen at the Fjord & Bælt facility in the harbor at Kerteminde, Denmark. The enclosure is situated in relatively shallow waters, with depths varying between 3 and 4 m. Vessel engine noise recordings were made from late morning to late afternoon and at a sea state <2 (smooth sea surface). As a noise source, we used a small (5-m) inboard-powered boat with a 2-stroke engine. The boat was moored outside the enclosure ~20 m from the outward side of the floating pontoon surrounding the pen. All procedures were monitored using an overhead video camera synchronized with the sound recordings. Care was taken to avoid recording any other boats passing within 500 m from the enclosure.

2.1 Mapping the Noise Field

A DTAG-3 multisensor tag was used to sample the noise field in the porpoise pen on a 2×2-m grid (Fig. 155.1, circles) at 3 depths: 0.5, 1.5, and 2.5 m. The tag recorded stereo sound with 16-bit resolution at 500 kHz and had a 1st-order high-pass filter with a cut-off frequency of 400 Hz. Additionally, five (one DTAG-3 and four hydrophone) reference stations were installed along the sides of the pen (Fig. 155.1, D-3 and H1–H4) to allow for correcting of any potential inter- and intrastation variations in the boat's source properties by matching the power spectral density levels recorded at a given reference station. The tag-synchronized reference hydrophones were lowered from the floating pontoon to a depth of 1.5 m. The received signals were

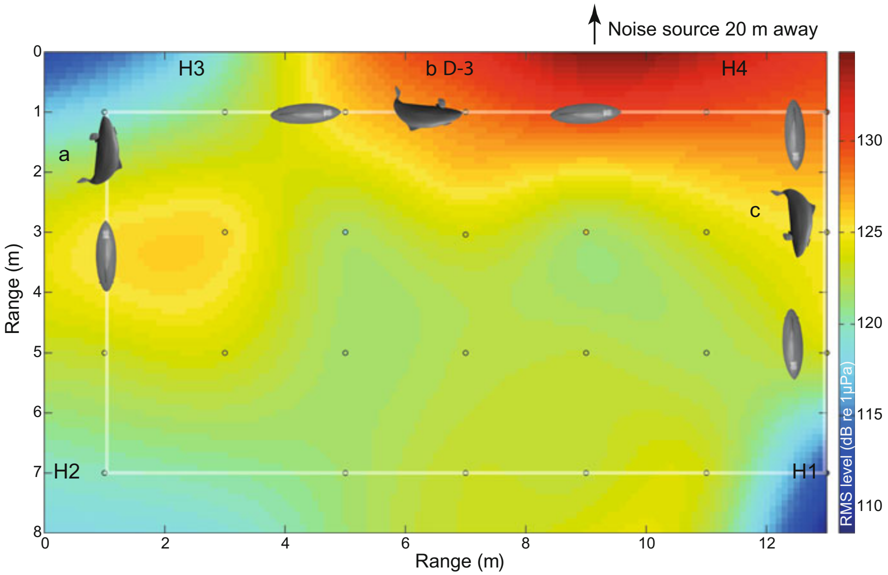

Fig. 155.1 Recording configuration and the acoustic field in the porpoise pen at a depth of 0.5 m during the noise exposure experiment. An inboard-powered boat was moored outside the enclosure ~20 m from the floating pontoon surrounding the pen. A DTAG-3 was used to sample the noise field in a 2×2-m grid (*circles*). Four reference stations (H1–H4), each equipped with a Reson TC4014 hydrophone at 1.5 m depth, were installed along the sides of the pen to correct for potential inter- and intrastation variations in source properties. The sampled root-mean-square (rms) pressure values were fitted with a surface (see Section . 155.2). Data outside the *white frame* were extrapolated. The porpoise's locations before (**a**), during (**b**), and after (**c**) the animal rolled in the sound field correspond to the subplots in Fig. 155.2

amplified and filtered using Reson VP 2,000 low-noise amplifiers or custom-made conditioning boxes (consistent throughout the recording period), and then simultaneously analog-to-digital (A/D) converted with 16-bit resolution at 500 kHz/channel (National Instruments USB-6356).

We calculated the root-mean-square (rms) noise level in a sliding window of 1 s for each of the DTAG-3 measurement stations (Fig. 155.1, circles) and fitted a surface to the reference-matched values using the MATLAB “gridfit” function with a grid spacing of 0.1 m.

2.2 *Testing the Reliability of Onboard Noise Recordings*

We deployed a DTAG-3 (with the same sound-recording settings as for the noise mapping) on a porpoise performing natural behaviors while being exposed to engine noise from the same boat moored to the same position. The animal was chasing fish, rolling and stationing at different water depths (to simulate bottom grubbing), while its movements were synchronously logged by the tag’s depth sensor, triaxial magnetometers, and accelerometers sampled at 625 Hz. The porpoise’s horizontal speed and position with respect to the sound source were monitored using overhead tag-synchronized cameras. We compared the onboard sound recordings with the noise field mapped at the nearest measurement station (Figs. 155.1 and 155.2).

To estimate the contribution of flow noise energy in the tag audio record, we used a reference DTAG-3 station (at b in Fig. 155.1) and repeated this experiment with no added boat noise.

3 Results

The acoustic noise field corrected for intra- and interstation variations showed a fairly uniform decrease away from the source with only little shading in the corners of the pen (Fig. 1), suggesting a reliable experimental setup and noise quantification method. Preliminary results indicate that flow noise limits tag-based noise quantification and that frequencies <200 Hz for animals swimming at <2 ms^{-1}, and higher for animals swimming faster, should not be considered in DTAG-3 recordings on harbor porpoises. No clear signs of body shading during rolling have so far been found for frequencies of 2–20 kHz (Fig. 155.2). This could be the result of the rolling movement being fast and therefore too short compared with the 1-s analytical window, causing an increase in flow noise, or it could be that DTAG-3 recordings are reliable regardless of body orientation. Further analysis and experiments with animals of different sizes are needed.

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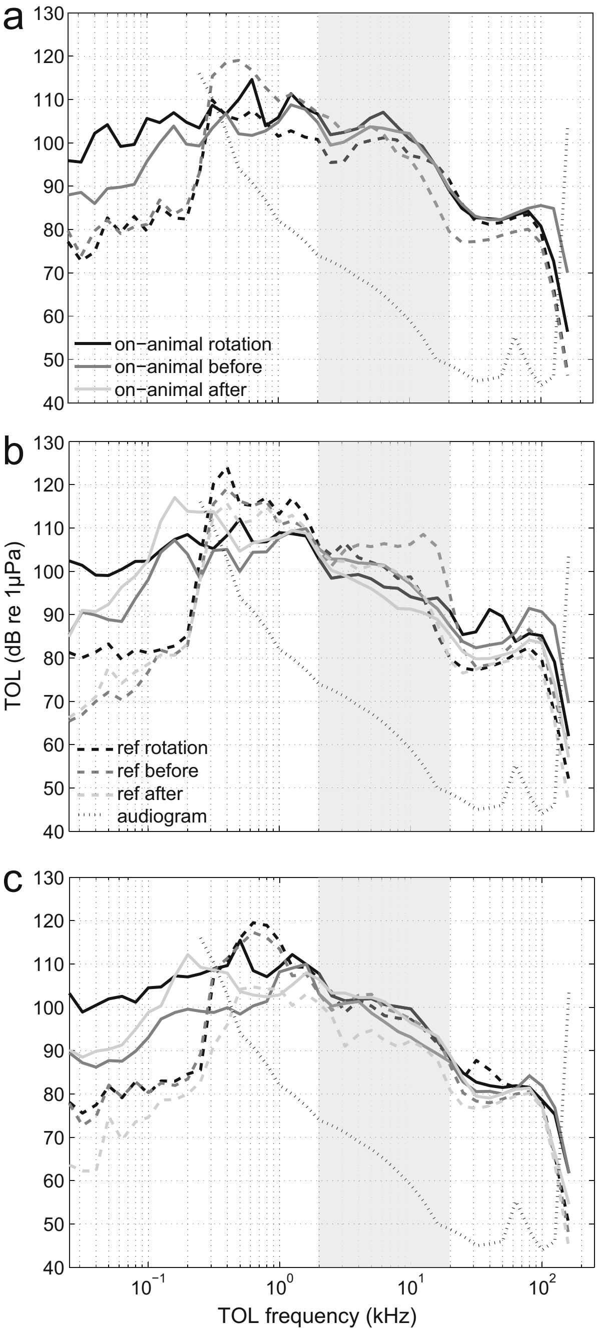

Fig. 155.2 Third-octave received levels (TOL) of noise recorded on the animal and at the nearest sampling station before (**a**), during (**b**), and after (**c**) the animal rolled in the sound field (as verified with the DTAG-3's accelerometers). A representative porpoise audiogram (mean 50% detection threshold as a function of center frequencies; Kastelein et al. 2010) is also shown. *Shaded area*, frequencies between the low-frequency by-product of sound generation (2 kHz; Hansen et al. 2008) recorded by the DTAG-3 whenever the animal is echolocating and the self-noise limit of the recording chain at the reference (ref) stations (20 kHz)

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Chapter 156

Development of a Model to Assess Masking Potential for Marine Mammals by the Use of Air Guns in Antarctic Waters

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Abstract We estimated the long-range effects of air gun array noise on marine mammal communication ranges in the Southern Ocean. Air gun impulses are subject to significant distortion during propagation, potentially resulting in a quasi-continuous sound. Propagation modeling to estimate the received waveform was conducted.

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A leaky integrator was used as a hearing model to assess communication masking in three species due to intermittent/continuous air gun sounds. Air gun noise is most probably changing from impulse to continuous noise between 1,000 and 2,000 km from the source, leading to a reduced communication range for, e.g., blue and fin whales up to 2,000 km from the source.

Keywords Mysticetes • Pinnipeds • Seismic • Propagation modeling

1 Introduction

Underwater noise is one of the sources of marine pollution whose ecological impact on marine mammals is not yet sufficiently investigated, although measurements in the northern Pacific indicate an increase in average broadband levels of ~10 dB during the last 35 years of the twentieth century (Andrew et al. 2002; McDonald et al. 2006). The possible impacts of underwater sound on the marine environment have been discussed, and concern is expressed in several publications (Richardson et al. 1995; Gordon et al. 2003; Southall et al. 2007; Weilgart 2007; Wright et al. 2007; Di Iorio and Clark 2009; Castellote et al. 2012; Melcón et al. 2012; Risch et al. 2012). Marine mammals of the Antarctic, although protected by the Antarctic Treaty System (ATS), are potentially affected by the use of high-power anthropogenic sound sources. Seismic air guns that are used for scientific seismic surveys in these areas produce high-intensity impulsive sounds with most of the energy in the very low frequency band that overlaps with many marine mammal vocalizations (e.g., songs and calls).

Marine mammals are highly dependent on their sense of hearing. The ability to acoustically perceive their environment is vital. Anthropogenic underwater noise may interfere with communication signals as well as predator, prey, or ambient sounds that are of importance to the animal and thereby mask an animal's ability to perceive these biologically important sounds (Erbe 2000; Clark et al. 2009). Air guns have also been considered as having potentially deleterious effects (e.g., physical harm, behavioral reactions) at short distances (Gordon et al. 1998; Yazvenko et al. 2007; Erbe and King 2009; Breitzke and Bohlen 2010; Gray and Van Waerebeek 2011). Masking as a far-reaching effect, however, was only partly considered within research studies and impact assessments, and only few studies have considered the potentially adverse effect that masking by air guns can have on marine mammals (Streever et al. 2012).

Air gun sounds can be perceived above ambient sound levels over vast distances in water. During the sound propagation process, impulses are reflected multiple times on the water surface and refracted in sound channels (Urick 1983). Due to these processes, the frequency content of the received signal at large distances as well as the length of the received waveform changes (signal stretching), which may cover the whole period between successive air gun shots. Hence, the impulsive sound that air guns emit can develop continuous properties through sound propagation effects and may lead to a general increase in background noise level and furthermore to continuous masking effects if the received levels are above the hearing thresholds of marine mammals.

This project aimed at evaluating the potential masking effects of scientific air gun use in Antarctica to provide a sound scientific basis for permitting of geophysical surveys. The first results of this project are presented in this paper.

2 Methodology

The evaluation whether there are potential masking effects was carried out in a three-step process based on a literature review about the species concerned, their vocalizations, possible overlap with scientific air gun use, and overlap in the frequency content of propagated air gun signals and animal vocalizations. The second step was sound propagation modeling, and last, the modeling of masking was carried out.

2.1 Sound Propagation Modeling

Sound propagation modeling was carried out for receiver positions at distances of 500, 1,000, and 2,000 km from the sound source using two flat-model ocean depths of 500 and 4,500 m on the basis of measured sound speed profiles. A third variable was receiver depth (10, 50, and 200 m were considered). The waveform of the air gun signal was taken from a previous study of an air gun array at a 10 m source depth and was converted to a frequency spectrum via a fast Fourier transform (FFT). The signal was then propagated with an acoustic toolbox user-interface and postprocessor (AcTUP) software to estimate transmission loss (TL), and the inverse FFT of the received signal was taken to reconstruct the waveform of the received air gun signal. Analysis was conducted using a mode summation algorithm that yielded similar results as a parabolic equation code but required less computing time. Water surface and sediment were assumed to be smooth. No damping was assumed. The results can therefore be considered as a maximum for the particular arrangement (source, receiver depth, and sound speed profile). Results indicate that there is very little energy above 300 Hz. The model shows that significant signal stretching can occur and will potentially lead to a continuous noise between 1,000 and 2,000 km from the air gun (Fig. 156.1) and beyond.

2.2 Masking Modeling

To limit the number of necessary calculations and restrict the analysis on species potentially affected, three model species were selected: blue whale (*Balaenoptera musculus intermedia*), fin whale (*Balaenoptera physalus*), and Weddell seal (*Leptonychotes weddellii*).

To take account of the impulsive nature of the air gun signals in different receiver distances (Fig. 156.1) and depth, it was decided that a model for the auditory processes would be necessary to characterize whether the communication signal of the

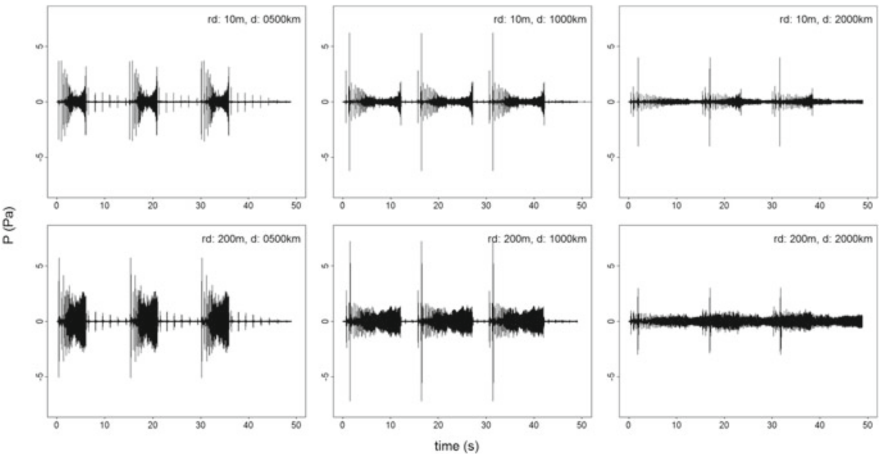

Fig. 156.1 Six input signals (seismic air gun) for the masking modeling for deep areas (4,500 m depth) at receiver depths (rd) of 10 and 200 m and distances (d) of 500, 1,000, and 2,000 km of a modeled impulse from an air gun. Pulses were repeated in 15-s intervals. Note how the stretched signal of the shots merge into each other to form a continuous, fluctuating signal

animals can be detected during air gun use. The model was chosen to be a leaky integrator (LI) and level detector because much better knowledge on baleen whale hearing is not available at the moment. For hearing thresholds, we assumed that baleen whales and seals are "noise limited" and hence hear any signal in the low modeled frequencies above background noise corresponding to sea state 3–4 [according to "Wenz" curves (Wenz 1962); from here on called "noise"; noise used in the modeling was actual background noise spectral density recorded at sea scaled to 80 dB re µPa root-mean-square (rms)].

The process covers the following steps. The propagated air gun signal and noise were overlaid and the LI was run on noise alone to estimate the LI output on noise alone (natural condition) and on noise overlaid with the air gun signal (masked condition). All signals were band-pass filtered in the same way as the animal vocalizations. The animal vocalizations were extracted from the recordings and were scaled to source level according to the literature. The duration and frequency bands were derived from the actual recording, band-pass filtered. A LI was designed using the duration of the signal as a time constant (case of best possible detection) and in the second step, the LI time constant was set to 0.2 s as a more reasonable estimate for the physiological time constant typical for mammals (Kastelein et al. 2010).

The LI outputs were compared and the masking distances were calculated. Examples of the spectrograms of the signals used are in Fig. 156.2.

Source levels of the vocalizations were taken from the literature for blue whales (179 dB re 1 µPa at 1 m; Samaran et al. 2010) and fin whales (189 dB re 1 µPa at 1 m; Širović et al. 2007) and were assumed to be a mean of the reported source level range of 173 dB re 1 µPa at 1 m for Weddell seals.

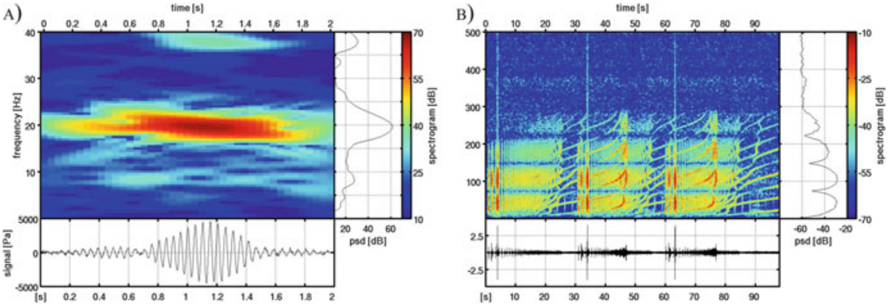

Fig. 156.2 Comparison of spectrograms of a fin whale's 20-Hz pulse scaled to source level (**a**) and the modeled outcome of the propagation model for air gun impulses for a receiver depth of 10 m at 2,000 km distance from the sound source (**b**). Overlays of these signals are used to estimate the distance at which the detection of the receiver is starting to be hampered by the interfering noise

3 Results

The results indicate that the communication distances for all three species considered are reduced at 500–2,000 km, but the effect strongly depends on the frequency of the vocalizations considered. For the three tested Weddell seal vocalizations, the estimated masking potential was highly variable, with unmasked communication distances ranging from 92% (essentially no masking) to 1% of the potentially undisturbed communication distance. For blue and fin whales, the communication range as modeled was reduced, ranging between one and two magnitudes.

4 Discussion

The results presented here are a first approach to predict the loss of acoustic communication range by seismic air guns. Given that all underlying assumptions are valid, the found reduction in available communication space would most probably have a serious effect. However, knowledge on baleen whale hearing capabilities is limited, and the data available for validating the sound propagation models in the receiver depths (mostly close under the water surface alike occurrence of baleen whales) are limited in bandwidth. Nevertheless, a serious model evaluation using real data has to be conducted before the results found in this study are used in a conservation context. Especially the modeled received levels of the air gun signal have a very strong influence on the masking model outcome and have to be considered as worst case estimates in this study. Hence, masking ranges are most probably overestimates. Critical information on baleen whale hearing such as, for instance, critical ratios and the ability to detect sounds from different angles of incidence in better accuracy will most probably alter the results.

It is evident that further research is needed; however, until more information and data are available for further model evaluation, a population-level effect of masking from seismic sources must be considered in conservation efforts. When the evaluation of the model is completed, it can be used for other species and provide guidance for the environmental assessment within the permitting process for scientific air gun use in Antarctica or other regions as well for nonscientific air gun use.

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Chapter 157
Review of Low-Level Bioacoustic Behavior in Wild Cetaceans: Conservation Implications of Possible Sleeping Behavior

Andrew J. Wright, Tomonari Akamatsu, Kim Nørgaard Mouritsen, Signe Sveegaard, Rune Dietz, and Jonas Teilmann

Abstract Shallow, low-activity, low-biosonar parabolic-shaped dives were observed in biologging data from tagged harbor porpoises in Danish waters and identified as potential sleeping behavior. This behavioral state merits consideration in assessing the context for noise exposure and passive acoustic monitoring studies. Similar dives have also been reported for other cetacean species. The existence of low-level bioacoustic dives that may represent that sleeping has implications for the mitigation of not only noise exposure but also of bycatch as well as legal repercussions given the protected status of sleeping, as a part of resting, under many legislative regimes.

Keywords Context • Response • Noise exposure • Bycatch • Passive acoustic monitoring

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1 Introduction

Noise pollution in the marine environment is increasing. In recent years, there has been a growing appreciation of the importance of the context in which an animal is exposed to noise in terms of the ultimate behavioral response and probably also the physiological impact (e.g., Ellison et al. 2011; Wright et al. 2011; New et al. 2013). One important element of this context is the activity of the animal, e.g., foraging, socializing, or even sleeping, although the latter behavior is currently largely unidentified in free-ranging cetaceans.

Although the majority of research on sleep in marine mammals has been undertaken in captivity (see the review by Lyamin et al. 2008), behavioral criteria for identifying sleep in wild animals have been established (Campbell and Tobler 1984; Tobler 1995). Wright et al. (2013) determined that it should be possible to identify any periods of reduced activity and stereotyped behaviors in data from biologging tags deployed on cetaceans as well as from any preferred habitat for sleeping (e.g., bottom or surface). Accordingly, Wright et al. (2013) identified parabolic-shaped dives as potential sleeping behavior using data from six biologging tags deployed on harbor porpoises (*Phocoena phocoena*) in Danish waters between May 2010 and August 2011. The rationale for this was the observed narrow range of shallow depths (around 6 m) at which these dives occurred (i.e., specific site) in combination with the significantly lower bioacoustic activity and the associated stereotyped, low-activity behavioral pattern. The stereotyped behavior observed was the smooth consistent movement of the animals through the parabolic dives with a slow continuous change of pitch, representing a continual change from the descent after one breath to the ascent toward the next. These dives contributed notably to the total time budget of the free-ranging porpoises (up to 10%; Wright et al. 2013).

Although surface logging is typically interpreted as “resting” behavior in wild cetaceans and may indeed represent sleeping, various subsurface periods of sleep have also been described in captive cetaceans (see the review by Lyamin et al. 2008). This should perhaps not be surprising because cetaceans engage in the unusual practice of unihemispherical sleeping where only half of the brain displays typical signs of sleeping, presumably as an adaptation to their aquatic life (e.g., Rattenborg et al. 2000; Siegel 2005; Lyamin et al. 2008). For example, captive bottlenose dolphins (*Tursiops truncatus*) have been reported to engage in stereotypic circular and/or slow up-and-down swimming (e.g., Mukhametov and Lyamin 1994; Sobel et al. 1994). Captive Commerson’s dolphins (*Cephalorhynchus commersonii*) have also displayed stereotyped circular swimming, with occasional episodes where they adopted a tail-up position for a few seconds (Mukhametov et al. 2001). However, it should be noted that the circular swimming behavior in both species may be merely an artifact of captivity (Sobel et al. 1994).

The possible existence of subsurface periods of sleeping in wild porpoises and other cetaceans would have a number of additional implications for assessing the impacts of noise in this species and potentially also other marine mammals. Furthermore, the porpoise is a species commonly thought to echolocate constantly (e.g., Verfuss et al. 2005; Cucknell et al. 2012; Nielsen et al. 2012). Thus the observed existence of dives with low levels of bioacoustic activity has a number of additional important implications for the wider study and conservation of wild porpoises. Here we discuss the various potential consequences of mobile subsurface sleeping behavior as well as the wider implications of the observed low-level bioacoustic dives regardless of their purpose.

2 Context of Exposure

The existence of periods of subsurface sleeping would mean that there are occasions where the animals would be less responsive to a certain level and type of sound exposure. However, it is likely that awakening would still occur once the sound exposure exceeded some threshold level (Campbell and Tobler 1984). It is possible that this would be associated with a startle response, inducing panic or inappropriate behaviors with any subsequent consequences these might have. For example, fear conditioning has been seen to result from repeated elicitation of the acoustic startle reflex in gray seals (*Halichoerus grypus*) as well as long-term shifts in behavior (Götz and Janik 2011). A further complication may stem from the fact that the level of sound required to bring a porpoise out of sleep may be variable, as is the case in humans who are more susceptible to being awoken by aircraft noise the longer they have been sleeping (Anderson and Miller 2007).

Second, the need for sleeping will influence the motivational state, especially given the need of most mammals to compensate for sleep loss (Tobler 1995; Cirelli and Tononi 2008). Accordingly, models that are built with the intention of estimating the comprehensive impacts of noise exposure must consider not only the consequences of noise exposure for sleeping animals but also the need for exposed animals to engage in sleep.

3 Impact Models

One approach for assessing the overall acoustic impact is through the use of energetic models (e.g., New et al. 2013), although these cannot directly incorporate factors relating to sleep loss. However, the possible existence of subsurface sleeping dives raises concern over any models that incorporate information from visually recorded behavioral activity budgets. Given the lack of logging behavior, it is likely that any low-level bioacoustic diving behavior in porpoises or other cetaceans (see Section 7) would have previously been interpreted as either travelling or foraging (perhaps as was the case in the bimodal diving patterns noted by Watson and Gaskin 1983). The result would be flawed interpretations of the total energy use of the animal and possibly also an overestimation of foraging time.

4 Ramp-Up

More directly, a lack of response during sleep would undermine the common sense logic behind one of the most commonplace mitigation techniques for seismic surveys, piledriving, and sonar activities: the ramp-up (also known as the soft start). The intention is to protect marine mammals by gradually building sound levels, relying heavily on the supposition that animals will move away from the increasing source before it becomes injurious to hearing. Then, once active, a moving source effectively functions as a continual ramp-up because sound levels rise ahead of the source as it approaches any given animal or area. However, if sleeping animals are unresponsive at normal levels, animals might not move away from an oncoming source in due time. This means not only that sleeping animals may have more extreme behavioral reactions (see Section 2) but may also be at a greater risk of being exposed to levels high enough to induce temporary or permanent threshold shifts in their hearing abilities.

5 Bycatch

Regardless of whether the parabolic dives actually do represent sleeping or not, there are also a number of implications arising from their general lack of bioacoustic signals. Harbor porpoises are known to be quiet sometimes when on the surface, like other cetaceans (Cucknell et al. 2012). However, dives with little or no sonar (Akamatsu et al. 2007; Linnenschmidt et al. 2013; Wright et al. 2013) can last for >20 min on some occasions (e.g., Linnenschmidt et al. 2013; Wright et al. 2013). This represents a period when the porpoises are likely to be at an increased risk of entanglement in set gill nets merely as a result of a reduced detection probability. However, risks may be further increased if the animal is in a state of reduced consciousness and awareness, such as sleeping.

Accordingly, the parabolic dives raise additional questions about the ability of porpoises to detect set gill nets and thus suggest that the extent to which they represent a threat may be underestimated (see a wider discussion in Nielsen et al. 2012). Although underscoring the need for measures to eliminate and/or mitigate bycatch, the finding also adds a note of caution regarding the use of interactive pingers that only produce sound in response to detection of cetacean biosonar signals.

6 Passive Acoustic Monitoring

The practice of employing passive acoustic monitoring (PAM) techniques for detecting porpoises has been used widely to estimate the abundance of marine mammals including the harbor porpoise (e.g., Kyhn et al. 2012). However, the processes of estimating abundance and/or assessing the impact of human activities through abundance comparisons may also be influenced by the presence of silent dives. For example, many PAM projects (e.g., Kyhn et al. 2012) have relied on the premise that harbor porpoises echolocate almost continuously for drawing their conclusions and estimating abundance. Accordingly, the existence of animals performing dives with little or no biosonar activity requires consideration in the assessments of abundance based on PAM. Similarly, any temporal patterns in sleeping/bioacoustic activity further complicate any PAM studies seeking to ascertain the extent of any avoidance impact arising from a given human disturbance.

7 Beyond the Harbor Porpoise

Beyond the work by Wright et al. (2013), only one study by Miller et al. (2008) with sperm whales (*Physeter macrocephalus*) has assessed the potential sleeping behavior in wild cetaceans. They reported that the whales take up an inactive vertical posture (sometimes switching between head down and head up) at or very close to the surface and typically do not respond to nearby vessels.

Although not interpreted as sleeping, low-biosonar dives with similar shapes have been reported in other cetaceans. For example, Akamatsu et al. (2010, p. 149, Fig. 2) reported the existence an upright dive with few clicks, no rolling, a parabolic shape, and a similar surge acceleration pattern in finless porpoise (*Neophocaena phocaenoides*). Furthermore, the postforaging shallow dives reported in beaked whales (Tyack et al. 2006; Aguilar De Soto et al. 2012) also have a striking similar shape accompanied by a lack of biosonar production. Additionally, shallow "respiration" dives that are often discarded as "noise" in the data may too be superficially similar in shape to those presented here (e.g., those presented between foraging dives in sperm whales by Watwood et al. 2006). Although several functions (e.g., for reducing oxygen debt of predator avoidance) have been suggested for these dives (see Tyack et al. 2006; Aguilar De Soto et al. 2012), none preclude a complementary role in sleeping (Wright et al. 2013).

Finally, other non-cetacean marine mammals have been seen to engage in the same unihemispherical sleeping (e.g., northern fur seal, *Callorhinus ursinus*: Mukhametov et al. 1985; manatees, *Trichechus manatus*: Mukhametov et al. 1992).

8 Legal Status

Sleep, and resting in general, are of interest because they have been recognized as behaviors of importance, with additional protections merited for resting animals (e.g., Ross et al. 2011). Thus, the discovery of sleeping dives may have repercussions regarding the extent to which disturbance from human activities at any given time, including through exposure to noise, can (or should) be allowed. For example, resting sites have been noted as worthy of special protection in various legislation around the world, including the European Union's Habitats Directive 92/43/EEC (European Commission 1992). The consequences of this are uncertain, however, because an improved knowledge regarding any specific geographic locations or habitat types of particular importance for this behavior will be needed before management action can reasonably be expected.

9 Conclusions

The discovery of low-level bioacoustic dives in harbor porpoises suggests that we currently underestimate the extent of the threat represented by bycatch as well as the capacity of interactive pingers to reduce it. However, we may also be underestimating the size of many populations because detection rates are likely to be lower than are currently presumed.

The existence of silent sleeping dives in harbor porpoises has a range of implications in a variety of areas in both science and management. Because similar dives may exist in other species, research in this area is of importance for marine mammal conservation and management in general. Should habitat ultimately be found unrelated to the occurrence of these shallow sleeping dives in porpoises (and other species) and only a particular depth found to be important to each species, a reevaluation of the legal definition of a "resting site" may be required. Much additional research in this area will be needed to address the many questions raised.

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Chapter 158
Noise-Dependent Fish Distribution in Kelp Beds

Xuguang Zhang, Hongy Guo, Zhenhua Wang, Yingjie Pan, and Jiakun Song

Abstract The marine marbled rockfish *Sebastiscus marmoratus* is dependent on kelp beds and rocks for survival and reproduction. We found that sound production and hearing sensitivity in *S. marmoratus* are closely matched in the frequency domain. We also found that the juvenile rockfish prefers the habitat of the larger macroalgae *Sargassum horueri* rather than the habitat containing the smaller algae *Ulva pertusa* where the adult rockfish prefers to live. Our underwater noise recording data from these two habitats indicate that their spectra of the background noise have different values. The results suggest that the acoustic cues may be critical for pelagic larvae when selecting the preferential habitat in which to settle.

Keywords Underwater noise • Rockfish • Habitat type • Settlement • Auditory evoked potential

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1 Introduction

In most marine ecosystems, many reef species (such as crustaceans and fishes) have a complex life cycle that includes a pelagic larval phase that disperses over great distances, and the pelagic larvae must select and settle back to the habitat of adults (Simpson et al. 2005). A number of studies have investigated that sound cues are used by larvae to locate their preferred settlement habitats such as macroalgae or coral heads (Simpson et al. 2005, 2010; Heenan et al. 2008; Stanley et al. 2012). The rockfish *Sebastiscus marmoratus* is a member of the Scorpaenidae family, being common on the rocky coast or kelp beds in southern China (Zhang et al. 2007). This fish inhabits the littoral rocky bottom and appears territorial, with small home ranges. During the spawning season, however, the females migrate from the shallow areas to deeper sites and release pelagic larvae (~4 mm total length; Fujita and Kohda 1998; Ng 2000). The pelagic larvae prefer to settle in different habitats; they do not return until grown to the adult stage. But, to date, it is not clear what cues are used by the larval fish in settling and returning back to habitats.

The rockfish *S. marmoratus* is well known for producing sounds using both sonic muscles and the swim bladder (Miyagawa and Takemura 1986). Calls of the fish can be recorded during aggression and spawning (Zhang et al. 2013). In this study, we investigated the hearing sensitivity of this species and the underwater noise of different coastal habitat types. We found that there were many differences in the spectral composition of ambient sound associated with different habitat types and that the fish distribution varied depending on fish age and the spectral characteristics of underwater noise in the kelp beds. This study provides some indirect evidence that sound cues should be used in the settling of larval fish.

2 Methods

The experimental protocols are briefly described. These protocols were designed to determine the relationship between fish distribution and the ambient noise of kelp beds in marbled rockfish. The fish were caught individually by hook line from the littoral reef area along Gouqi Island, Zhejiang Province, China (122 caught individually by an ~5 m hook line). Sexes were not discernible due to a lack of sexual dimorphism. All animal protocols were approved by the Review Committee for the Use of Animal Subjects of Shanghai Ocean University.

2.1 Sound Production

Sound recordings of wild marbled rockfish, *S. marmoratus,* were conducted in a walk-in soundproof room in a canvas tank. A plastic rod was lowered by a manipulator to gently prod the fish to induce disturbance sounds. Sound pulses of disturbance and advertisement calls of the fish have similar characteristics. Such data of sounds are important to guarantee species identification during sound recordings in the wild.

The voluntary sounds emitted by a school of free-swimming fish were also recorded in a big canvas holding tank. Sounds were recorded using a preamplified BII-8000 hydrophone (sensitivity −185 dB re 1 V/µPa; frequency response 1 Hz to 24 kHz; Benthowave Instruments, Inc.) and were analyzed with Praat Bioacoustics software (version 5.3.03; freely available at http://www.praat.org) to determine the spectral composition.

2.2 Auditory Sensitivity

Auditory sensitivity was measured using the auditory evoked potential (AEP) recording technique described by Kenyon et al. (1998). Sounds were played and AEP responses were collected using a TDT physiological apparatus (model RZ6, Tucker-Davis Technologies) and analyzed with SigGen and BioSig software. Stimuli were generated by TDT software through a power amplifier connected to a UW-30 underwater speaker. The test tank acoustic output calibration was performed using a Brüel & Kjær 8,103 hydrophone. Test signals were pure tones in the frequency range from 100 to 2,000 Hz, and sound intensity levels at each frequency were increased in 4-dB steps from 60 to 130 dB until a typical AEP waveform was observed.

2.3 Fish Distribution and Ambient Kelp Bed Noise

The distribution of fish assemblage was conducted in the kelp beds of Gouqi Island. There were three habitat types with 2–4 different sites for each habitat: larger macroalgae (LM) *Sargassum horueri*, smaller algae (SA) *Ulva pertusa*, and open sand beach (OS). The abundance of fish was surveyed on a monthly basis. At each location, the fish were sampled for 2 h using two fixation trammel nets. The index of relative importance (IRI) was used to classify the dominant fish assemblages in the three habitat types (Zhang et al. 2011). This value of IRI is more than 1,000 for dominant species. The kelp bed noise was recorded using a floating hydrophone system hydrophone (sensitivity −185 dB re 1 V/µPa; frequency response 1 Hz to 24 kHz; BII-8000, Benthowave Instruments, Inc.) to reduce extraneous noises. A recording of 5 min in duration was made between 1,200 and 1,300 h at each habitat. The digital recordings were transferred to a personal computer and analyzed with Praat Bioacoustics software.

3 Results

Three distinct sounds of *S. marmoratus* were recorded. In disturbance experiments, the fish produced two types of sounds, and in free-swimming conditions, the fish produced only one kind of sound. Common characteristics of all recorded sounds were that they were pulselike and low frequency (below 200 Hz). The mean dominant frequency of the voluntary sounds was 53 ± 5.2 Hz, the pulse duration was 115 ± 25.9 ms, and the interpulse interval was 1,100 ± 910 ms.

The disturbance sounds were composed of a series of individual pulses, with a mean dominant frequency of 172 ± 2.5 Hz, a pulse duration of 28 ± 2.8 ms, and an interpulse interval of 69 ± 103 ms (ranging from 1 to 300 ms; the last interval almost approaching 0). There was a significant difference in the dominant frequency in the two types of sounds (Mann-Whitney rank test, $P < 0.001$).

AEPs were obtained from five rockfish, and averaged response traces within a frequency were similar among all individuals tested. Mean auditory thresholds for all fish showed that *S. marmoratus* is most sensitive to low frequencies, with a best frequency at 100–400 Hz. The dominant fish were *S. marmoratus* (11.3% of total abundance = 4,263), *Agrammus agrammus* (9.4%, IRI = 1,844), and *Nibea albiflora* (10.9%, IRI = 1,237) in all habitat types. The fish with the sexual gland in development in phase II were defined as juvenile fish. The juvenile rockfish accounted for 67.1% of the total abundance in the LM habitat type and 39.5% and 8.3% in the SA and OS habitats, respectively. Analysis of the stomach contents showed that the small benthic invertebrates, such as *Orchestia* sp., *Caprellidea* sp., and *Ligia exotica*, were the dominant foods of rockfish. The passive acoustic recording showed that the spectra for the three habitat types were different. The noise of the LM habitat type had a higher power level in the frequency band from 500 to 3,000 Hz, whereas there was a low-frequency band from 100 to 500 Hz in the SA and OS sites. The 100–500 Hz band was due to small waves, some fish species, and low-frequency noise from shipping. The 500–3,000 Hz band may be produced from small benthic invertebrates described by other reports. The recording also showed that shipping noise would increase the sound power level in the low-frequency band. But the increase in power level in the LM habitat was 10.5 ± 7.4 dB less than the value of 19.5 ± 11.5 dB in the SA and OS sites from 100 to 5,000 Hz (Fig. 158.1). It suggested that the kelp bed or kelp forest dominated by the LM *Sargassum horueri* has a baffling effect on noise from the boat or other resources.

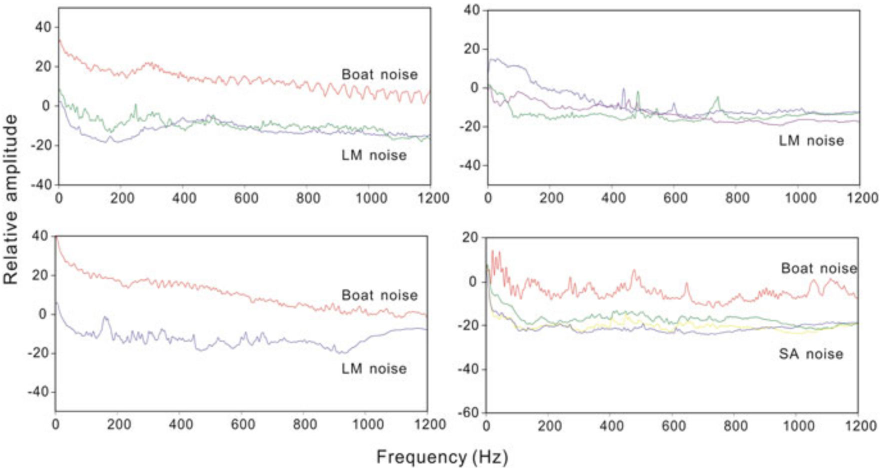

Fig. 158.1 Underwater noise from kelp beds of larger macroalgae (LM) *Sargassum horueri* and smaller algae (SA) *Ulva pertusa. Red line* represents boat noise recorded in the kelp beds; other *color lines* represent noise at different times in the kelp beds. Note that the amplitude of the boat noise in the SA kelp bed is larger than the boat noise in the LM kelp bed

4 Discussion

Because many rock reef-dwelling larvae are known to be capable of preferentially arriving at settlement habitats, a number of studies have investigated what cues are used by larvae to locate these preferred settlement habitats. The ambient underwater sound has long been regarded as one of most robust candidates for guiding some pelagic larval fishes to settlement habitats on coastal rock reefs (Simpson et al. 2010). The marbled rockfish inhabits on the littoral rocky bottom and appears territorial, with small home ranges, but the pelagic larvae dispersed over great distances from the habitats of the adult. In the present study, we demonstrated that the sound production and hearing sensitivity of this species; the matching of spectra in sound production and hearing, indicating that the acoustic information is important for communication among rockfish; and the sound cues would play key roles in settlement.

Many marine species are dependent on rocks and kelp beds for survival and reproduction. The juvenile marbled rockfish preference for LM *Sargassum horueri* habitats observed in this study is due to the abundance of invertebrates. Kelp beds have been documented to support complex near-shore food webs and the invertebrates must rely on the biodetritus produced by algae and other aquatic organisms in kelp beds (Willis and Anderson 2003). Noise of 500–3,000 Hz in LM habitats may be produced by small benthic invertebrates, but some noises in the 100–500 Hz band should be from fish species including adult marbled rockfish and other sonic croakers (Ramcharitar et al. 2006; Zhang et al. 2007; Radford et al. 2010). It suggested that there was an adaptive avoidance of smaller algae habitats in juvenile marbled rockfish.

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Chapter 159
Summary Report Panel 1: The Need for Protocols and Standards in Research on Underwater Noise Impacts on Marine Life

Christine Erbe, Michael A. Ainslie, Christ A.F. de Jong, Roberto Racca, and Michael Stocker

Abstract As concern about anthropogenic noise and its impacts on marine fauna is increasing around the globe, data are being compared across populations, species, noise sources, geographic regions, and time. However, much of the raw and processed data are not comparable due to differences in measurement methodology, analysis and reporting, and a lack of metadata. Common protocols and more formal, international standards are needed to ensure the effectiveness of research, conservation, regulation and practice, and unambiguous communication of information and ideas. Developing standards takes time and effort, is largely driven by a few expert volunteers, and would benefit from stakeholders' contribution and support.

Keywords Standards • Protocols • Acoustic terminology • Acoustic quantities • Bioacoustic procedures • ISO

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1 Introduction

Research on the impacts of underwater noise on marine life appears to be steadily increasing. Unfortunately, results are not readily comparable. Scientists use different experimental equipment and procedures, different algorithms for analysis, and different terminology, quantities, and units. Common protocols for data collection, analysis, and reporting are needed so that data can be compared or synthesized across multiple studies. A panel discussion was held at the Third International Conference on the Effects of Noise on Aquatic Life, in Budapest, Hungary, on 11–16 August 2013. The objectives were to identify existing protocols and standards for the measurement and reporting of underwater sound and bioacoustic impacts, to identify critical gaps, and to discuss how such gaps could best be filled. This article reviews the history of standardization in underwater acoustics, and summarizes the panel presentations and whole audience discussion.

2 Terminology for Underwater Sound

> Every science requires a special language because every science has its own ideas. It seems that one ought to begin by composing this language, but people begin by speaking and writing and the language remains to be composed.—Étienne Bonnot de Condillac (1715–1780; Fig. 159.1)

Fig. 159.1 Étienne Bonnot de Condillac (1715–1780)

Early progress in the standardization of underwater acoustical terminology includes the American National Standards Institute (ANSI S1.1-1994) *Acoustical Terminology* and Carey's (1995) IEEE editorial *Standard Definitions for Sound Levels in the Ocean*. At about the same time, Hall (1995) pointed out the need for clarity and consistency with SI in dimensions and units. An important step forward was made by Morfey's (2001) *Dictionary of Acoustics*, but there was relatively little progress specific to underwater sound until the European Union's Marine Strategy Framework Directive (European Union 2008) sparked renewed interest in the subject throughout Europe by including underwater noise explicitly as one of 11 descriptors of good environmental status (European Union 2010). Realization of the urgent need for a common terminology standard resulted in an ad hoc collaboration between European scientists, culminating in a consensus report published by the Netherlands Organization for Applied Scientific Research (TNO; Ainslie 2011) that has since been adopted for international collaboration both in the European Union (Dekeling et al. 2013) and worldwide (Boyd et al. 2011). In the United States *Acoustical Terminology* is currently undergoing a thorough revision under the chairmanship of Jeff Vipperman and Charles Greene, with a revision expected in early 2014.

In 2011, the Acoustics Technical Committee of the International Organization for Standardization (ISO) established a subcommittee, chaired by George Frisk, dedicated exclusively to underwater acoustics, which held its inaugural meeting at the Woods Hole Oceanographic Institution in June 2012. The current standards secretary for the Underwater Acoustics Subcommittee (ISO/TC 43/SC 3; Fig. 159.2) is Susan Blaeser (sblaeser@aip.org).

In 2012, ISO's Technical Committee 43, Subcommittee 3, Working Group 2 (ISO/TC 43/SC 3/WG 2) on Underwater Acoustical Terminology was formed under the leadership of Michael Ainslie. This working group (WG) met twice in 2013, and then in 2014. The goal is to release a new international terminology standard in 2015.

This ISO WG is attempting to standardize the definitions of some of the most common quantities in underwater acoustics, such as sound pressure level (SPL). At the moment, ANSI S1.1-1994 defines the SPL as $10\log_{10}(p^2_{\mathrm{rms}}/p^2_{\mathrm{ref}})$, whereas

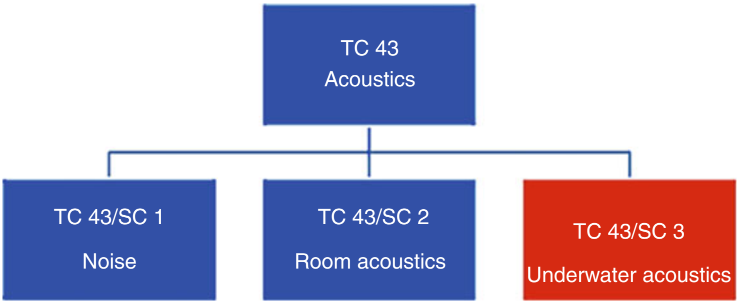

Fig. 159.2 International organization for standardization (ISO)/TC 43 (acoustics) and ISO/TC 43/SC 3 (underwater acoustics)

ISO 80000-8:2007 gives SPL as $10\log_{10}[p(t)^2/p^2_{\mathrm{ref}}]$, where $p(t)$ is the instantaneous sound pressure, p_{rms} is the root-mean-square value of $p(t)$, and p_{ref} is the reference pressure (1 μPa). The WG is seeking international consensus on how this term is used in underwater acoustics. Its remit does not end there, but extends also to bioacoustical terminology (e.g., critical ratio, temporary threshold shift) and the terms of the sonar equation such as source level, detection threshold, and array gain, many of which are in widespread use by bioacousticians.

The "source level" is a far-field property of the source. In the bioacoustics literature, it is expressed by a multitude of quantities such as rms SPL, peak-to-peak SPL, and sound exposure level. Different definitions would be sensible for different sources such as transient (e.g., seismic air gun) versus continuous (e.g., dredger) sources or near-surface sources (e.g., ships) versus sources at depth (e.g., whales). Many measurements report a radiated noise level (RNL), which is the sum of the SPL measured in the far field at range r plus a geometric spreading term: $\mathrm{RNL} = \mathrm{SPL}(r) + 20\log_{10}(r/1\ \mathrm{m})$. RNL is affected by the propagation conditions (water depth, hydroacoustics, seafloor geoacoustics) and the measurement geometry. It is not a level that can be plugged into sound propagation models to predict the noise footprint of a similar source in a different environment. Sound propagation models require monopole source levels, which are computed by back-propagating a spectrum recorded in the far field to a nominal distance of 1 m from an "equivalent" point source, by using a sound propagation model that adequately accounts for the specific propagation environment. Unfortunately, RNL is often misused as a monopole source level, leading to severe errors in noise prediction.

Further confusion is caused by terms such as "transmission loss" and "propagation loss," sometimes used synonymously (and sometimes not) to represent ratios of sound intensity, sometimes with and sometimes without corresponding impedance ratios, and rarely defined explicitly (Ainslie and Morfey 2005).

The absence of standardization places the onus on individual authors, if ambiguity is to be avoided, to state definitions each and every time they are used. Having a standard will facilitate the reporting of quantities by replacing the list of definitions with a single reference. Stakeholder participation is essential to ensure that the necessary terms are included in the ISO standard.

3 Measurement of Underwater Sound

Different procedures are used for the characterization of underwater sound because the sources vary, the users vary (military, industry, regulatory bodies, environmental groups), and the applications vary (comparing sources against each other or against limiting values, providing input for sound-propagation models). One standard is likely not going to suit all purposes and should detail the specific applications.

Within ISO/TC 43/SC 3, two WGs are focusing on the measurement of underwater sound: WG1 on the measurement of underwater sound from ships led by Michael Bahtiarian and WG3 on the measurement of radiated noise from marine pile driving led by Stephen Robinson, which had its inaugural meeting in May 2013. The basis for WG1 has been the existing ANSI S12.64-2009/Part 1 standard on *Quantities and Procedures for the Description and Measurement of Underwater Sound from Ships—Part 1*: *General Requirements*. This standard yields a RNL useful for the comparison of received levels from different ships. There is a similar WG within TC 8, *Ships and Marine Technology*/SC2, *Marine Environment Protection* working toward a standard on the measurement and reporting of underwater sound radiated from merchant ships led by Koichi Yoshida.

A list of additional work items has been registered at the ISO, for which conveners and WG members are still lacking: measurement of ambient underwater noise, measurement of underwater sound from active sonars, measurement of underwater sound from air guns, underwater sound propagation modeling, measurement of underwater sound fields, and underwater noise mapping.

4 Biological Data Collection

As far as we are aware, there are currently no standards for the measurement, analysis, and reporting of biological data as related to studies of underwater noise impacts on marine fauna. Conformity on even basic terminology (and computation of associated quantities) such as mean dive time or respiration rate is lacking. One complication is that the type of data that can be collected is highly species and situation dependent. Southall et al. (2007) compiled a severity score (0–9) for ranking observed behavioral responses from minor to moderate and severe. No numerical quantification of these adjectives is given in terms of their biological significance, however, and any such quantification would likely need to be expressed in terms of the “normal” variance of behavior. Baseline data required to define this intrinsic variance are mostly insufficient and problematic to establish due to the multivariate nature of behavior and its dependence on environmental factors at the specific time and place. Environmental factors are more easily controlled when working on small animals (e.g., fish or larvae) in captivity; protocols and standards for tank experiments, however, are lacking as well.

The gray whale monitoring and impact mitigation program adopted for a 2010 4-dimension (4-D) seismic survey by Sakhalin Energy Development Company was designed by a multistakeholder panel of experts and included protocols for theodolite tracking of whales during seismic surveys, received sound level monitoring at multiple sites, and mitigation (shutdown) procedures based on real-time estimation of received levels. The Joint Nature Conservation Committee in the United Kingdom has developed protocols for minimizing the risk of injury to marine mammals from seismic surveys and pile driving, outlining a series of steps from the planning stage to the operational stage and the reporting stage. There are requirements for marine mammal observers and their training, equipment and reports and for passive acoustic monitoring. The protocols further describe the implementation of mitigation zones, soft starts, and delays. These are all examples of carefully conceived methodologies that could form the basis of standardized approaches.

5 The Standardization Process

The ISO provides a platform for the development of technical standards that address the needs of multiple stakeholders. Members of the ISO are countries represented by the national standards body of each country. Each country has one vote. As a first step, the need for a new standard is identified by any person or group and communicated to their national member body. A proposal for a new work item is submitted by that member body for vote by the members of the appropriate technical committee. Given a majority vote and a minimum of five member bodies declaring their commitment to actively participate in the development, an international WG of experts is established under the leadership of a chairman or convener. This WG develops a draft standard, which is sent to all ISO members for voting (see http://www.iso.org/iso/home/standards_development/resources-for-technical-work/stages_of_the_development_of_international_standards.htm). The resulting ISO standards are voluntary; they are offered for adoption by industry and other stakeholders. Some standards might eventually become mandatory in certain regions if they are adopted by local regulators as legal requirements.

The development of an ISO standard is a slow process, partly because WG experts participate on a voluntary basis and partly because of the need to secure international consensus. Because experts are drawn from multiple countries, most communication happens by email, with occasional online meetings across all time zones. WG experts typically lack financial support for face-to-face meetings, which could speed up the process.

There is widespread concern that the absence of standardization might reduce the value of the considerable resources spent on characterizing anthropogenic noise for bioacoustic impact assessments. However, if acoustic signals are sufficiently well sampled and metadata (on the source, the observations, and the environment) are properly recorded, original time series can be later reprocessed according to new insights, requirements, or standards.

There is concern by some within the marine bioacoustics community, expressed during the panel discussion, that ISO standards (e.g., for the measurement of ship noise) are driven by engineering professionals outside the field of marine bioacoustics and as a result are becoming too demanding in terms of equipment, field work, and data-processing resources to the extent where a large part of the bioacoustics community will not be able to collect data of “acceptable” quality. However, the existing standards were developed with a different application in mind, and the specific requirements for the bioacoustics community could be met in alternative standards that are fit for that purpose. Others voice an opposite concern that inadequately defined standards may foil the data-collection efforts of many researchers by not prescribing the necessary quality of instrumentation and rigor of procedures required to yield a consistent quality of data.

A solution to enhance relevance to the community and to speed up the standardization process would be for expert bioacousticians to join the appropriate WG and for other stakeholders (e.g., from industry, military, or government) to contribute financial support for a group of experts to convene, to consult with the broader community, and to develop protocols that are specific to the interests and needs of all concerned. Such protocols could eventually become the background document for a new work item at ISO.

6 Conclusions

Marine bioacoustic standards will not be developed without effort. Stakeholders are invited to take the initiative and/or contribute to standard development. Given the huge expense in terms of human and financial resources and time, in particular when studying megafauna in the wild, a lack of protocols and standards is an unacceptable loss for science, industry, and government and for the environment.

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Chapter 160
Summary Report Panel 2: Regulatory Issues

Craig Johnson and Sarah Dolman

Keywords Noise • Regulation

1 Introduction

The Effects of Noise on Aquatic Life 2013 Conference convened four panels to discuss specific topics related to the effects of anthropogenic noise on aquatic ecosystems. The second of these four panels, the Regulatory Issues Panel, brought together several different perspectives: representatives of agencies responsible for regulating activities that introduce anthropogenic noise into aquatic ecosystems: representatives of the regulated industries, agencies, and consultancies that advise regulators and regulated industries; and nongovernmental organizations and other stakeholders with an interest in anthropogenic noise. The goal of the panel was to help develop a more productive relationship between these groups.

The Regulatory Issues Panel started with presentations from three panelists: Sarah Dolman (Whale and Dolphin Conservation, United Kingdom), Bill Streever (BP Exploration, Alaska, Inc., United States), and Mark Tasker (Joint Nature Conservation Committee, United Kingdom). Craig Johnson (formerly of the US National Marine Fisheries Service) chaired and moderated the discussion.

Each of the panelist's 5-min presentation was designed to facilitation a discussion between the panelists and the audience. The panelists' presentations raised a number of shared concerns and captured several of the central issues associated with whether current approaches to regulating anthropogenic noise fulfill their purposes, including whether scientific information and understanding is being

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translated into effective policy or providing guidance that can be used effectively by regulators and the regulated industries; whether guidance is being reviewed and revised in a timely manner to ensure that it reflects new scientific understanding; whether scientific knowledge and monitoring inform the various kinds of environmental assessments that regulatory agencies, developers, and consultancies conduct on noise-producing activities; the adequacy of attempts to assess the accumulative effects of noise; whether regulatory effort should focus on particular groups of species (for example, marine mammals, marine birds and their habitats, endangered species) or ecosystems, which would capture cumulative impacts; and how regulatory agencies and regulated industries can share knowledge and experience while respecting the diversity of their mandates and cultural perspectives.

2 Discussion Summary

After the panelists' presentations, the following questions were presented before the discussion was opened to the floor.

(1) What are the purposes of regulating anthropogenic noise? Is it intended to protect aquatic biota from suffering adverse consequence as a result of acoustic exposures or something else (for example, to protect aquatic ecosystems from acoustic energy)?
(2) If regulation is intended to protect aquatic biota, what adverse consequences should regulation prevent? Is it intended to prevent aquatic biota from experiencing changes in hearing sensitivity, is it intended to prevent populations of aquatic biota from experiencing declines as a result of being exposed to anthropogenic noise, or is it something else? If regulation is not intended to protect aquatic biota from suffering adverse consequence, what outcomes should regulation prevent?
(3) What noise-generating activities should regulation consider or prioritize?
(4) What are the purposes of mitigation?
(5) What mitigation approaches best achieve those purposes?

Once the audience joined the discussion, topics shifted from speaker to speaker. However, several common themes emerged.

(1) In many cases, statutes and legal mandates specify what they protect (individuals, populations, species, or ecosystems) and what adverse effects regulators are directed to avoid. Problems emerge when statutes do not specify what is protected and what outcomes need to be avoided. In these cases, the group leaned toward protecting aquatic species and populations, particularly species of animals, from the adverse effects of anthropogenic noise rather than protecting aquatic ecosystems from those effects. The group did not reach common agreement on whether regulation should try to avoid adverse effects on (1) animal welfare (for example, quality of life, general health); (2) the fitness or

ecological performance of individual animals (for example, reductions in longevity or reproductive success); (3) "take" of individual animals, which encompasses both animal welfare and individual fitness; or (4) the ecological performance of populations or species (including reductions in viability).

(2) Regulatory efforts should adequately balance protecting aquatic species and ecosystems with the economic interests of industry and other regulated parties. Ensuring that regulatory requirements, which include mitigation and monitoring, are clearer, consistent, and coherent from one jurisdiction to another would make it easier for industry to plan and prepare to meet those requirements.

(3) Regulation should provide industry with clear, simple, coherent requirements that are based on sound, scientific evidence; regulatory requirements should be tailored to particular ocean basins or river systems; there should be guidelines or frameworks that industry can employ in unregulated areas; and regulatory requirements should be updated to reflect new scientific understanding as it becomes available using procedures that are transparent to regulated industries, other stakeholders, and the public.

Several participants cited the approach that Germany uses to regulate anthropogenic noise resulting from pile driving for offshore marine renewable energy as an example of a clear and simple approach to regulation that is based on science. Regulatory agencies should also consider alternative approaches, alternatives to setting specific numeric standards, for regulating activities that produce anthropogenic noise. Examples included the approach agencies in Australia use to regulate anthropogenic noise and approaches the US Environmental Protection Agency uses to regulate point and nonpoint sources of air and water pollution.

The principles of clarity, coherence, and being founded on sound science should also apply to the frameworks regulatory agencies use to assess the risks anthropogenic sound poses to individual animals, populations, species, and ecosystems.

(4) Regulatory agencies in many sovereign nations still have not focused on the effects of anthropogenic noise on aquatic ecosystems or have much less experience than agencies in other nations. To ensure that regulators have a common understanding of the science on which regulation should be based, it would help to establish mechanisms for communicating the science to the public, industry, stakeholders, media, and regulators who have not yet focused on acoustic issues. It would also help to establish mechanisms that allow regulators with less experience to learn from agencies and organizations with more experience.

(5) Regulatory agencies, regulated industries, and other stakeholders should devote more effort to communicating the results of scientific study and industry practices to the public. This kind of communication will help to inform, with the view to combat much of the controversy and conflict surrounding proposals to introduce anthropogenic noise in aquatic ecosystems and the effects of those proposals on populations, species, and ecosystems.

(6) Current regulatory efforts have tended to focus on point sources of anthropogenic noise (that is, noise produced by specific activities in known locations), but they also need to address "nonpoint" sources of anthropogenic noise.

Toward the end of the session, several members of the audience pointed to the substantial progress that has occurred over the past decade: heightened awareness of the potential risks of anthropogenic sound in aquatic ecosystems, development of regulatory approaches that can evolve as scientific knowledge advances and are adaptable to specific circumstances, and stronger, more cooperative interactions between regulators, regulated industries, and other stakeholders.

Chapter 161
Summary Report Panel 3: Gap Analysis from the Perspective of Animal Biology: Results of the Panel Discussion from the Third International Conference on the Effects of Noise on Aquatic Life

Jill Lewandowski, Joseph Luczkovich, Douglas Cato, and Rebecca Dunlop

Keywords Panel • Biological • Data gaps • Marine mammals • Sea turtles • Fish • Fisheries • Invertebrates

1 Introduction

There is little disagreement among regulators, scientists, and other interested parties as to the complexity surrounding our understanding of the potential and realized impacts of anthropogenic noise on marine life. Given the challenges of research in an aquatic environment, the breadth of species of interest and the range of human-made noise-producing activities, it is difficult at best to identify the most important science needs that improve our understanding and ultimately regulation of the issue.

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This panel session set forth to gather input as to the key science needs for addressing ocean noise. Approximately 40–50 stakeholders participated in this session. The panelists first provided a short overview of their recommended key science needs. The session then divided into two "biological" groups, marine mammals and sea turtles (facilitated by Jill Lewandowski) and fish, fisheries, and invertebrates (facilitated by Joe Luczkovich). The remainder of the session was devoted to the two sub group discussions aimed at identifying (1) key baseline data needs and research questions, (2) potential representative species, and (3) prioritization of data needs and research questions. The following information provides an outline of the outcome of the discussion.

2 Marine Mammals

There was a clear sense among many of the subgroup participants that the overall research direction for marine mammals has moved away from baseline information needs, largely due to funding groups pushing for "applied" science. There clearly needs to be a better understanding among researchers and funding groups as to what constitutes applied science given that baseline biological information is always needed to answer the more complex questions of noise. With this in mind, participants offered the suggestions listed below for addressing baseline biological data needs.

- Population monitoring and impact probabilities
  - Need easier metrics to detect changes in population and to track over time
- Population impact probabilities
  - Which species are most likely to be susceptible within a given habitat?
  - What sources are deployed there?
  - Look beyond only the endangered species
- Combine hearing and behavioral studies
- More audiograms for more species (especially mysticetes)
  - There are audiograms for only 17 of 85 species!
  - Need to get access to stranded animals to obtain audiograms on more individuals and species
  - Consider studies that evoke a temporary threshold shift (TTS) by using natural sounds as a stimulus to test injury without introducing new sounds
- Tease apart multiple stressors to understand what is actually affecting animals
- Better understand aversive sounds and basic processes like startle, sensitization, habituation, and annoyance
- Move away from just addressing immediate needs
  - Plan in 5–10-year horizons but also address more urgent needs within plan
  - Need a balanced portfolio, enough immediate efforts but also longer term
  - Conduct longitudinal studies on individual animals

  What are animals actually experiencing as they move (versus existing studies on effects at one space and point in time)?
  Further develop and apply long-term acoustic tags on animals

- Contextual influence of response
  - How do animals respond to large variations in natural sounds?
  - How does this compare with anthropogenic noise responses?
  - How do they functionally hear?
  - How do animals extract signals from noise?
  - How do they perceive the auditory scene?
  - How do they learn from past noise exposure?
  - What are the hearing and masking profiles?
  - What has natural selection highlighted as most important capabilities and how does affect those specific adaptations?
- Look at more interdisciplinary, ecological-scale studies with longer-term focus
  - Don't work in your own little group, collaborate!
  - Convene more interdisciplinary synthesis meetings for groups working on common topics
  - Consider oceanographic conditions
  - Need to understand what is happening to prey and develop better methods to understand foraging (e.g., better instrumentation and interdisciplinary research)
- What will the effects of climate change do to animals and acoustic habitats?
- Need a repository of existing baseline and acoustic data
- Need a database of what we do not know
  - Could be moderated so people can access and see what is needed
- Need a new discipline that specializes in combining all of this knowledge (e.g., experts who can assimilate the biological and physical aspects of issue) or develop interdisciplinary teams
- Need better basic risk assessment built on better baseline data
- Need more sophisticated statistical approaches
- Need to better connect scientists with regulators and ocean user communities
- Academics need to better understand regulatory process

3 Sea Turtles

Another theme that was consistent through the discussion was related to the significant lack of information on noise impacts on sea turtles. There have been only a few studies on sea turtle hearing, and these have been confined to only one age group and one or two species. Our understanding of sea turtle hearing and the potential impacts of noise is, at best, in its infancy, and research needs to start with the basics (e.g., hearing studies on all species across several age and sex classes).

4 Fish, Fisheries, and Invertebrates

It was clear from the overall conference that the knowledge of fish hearing and the potential impacts of ocean noise has grown considerably in recent years. Invertebrate hearing, like that of sea turtles, is still in its infancy, and little is known about the effects of noise versus particle motion or ground roll. Overall, many key questions still remain unanswered for fish, fisheries, and invertebrates.

- What is the threshold for behavioral response?
- Priority species and groups
  - Food web species for marine mammals
  - Base of food web
  - US Endangered Species Act and International Union for Conservation of Nature listed (sturgeon and salmon)
  - Cephalopods! And all other invertebrates (huge species diversity and major gap)
  - Anadromous species
  - Swim bladder: Physotomes/Physoclists
  - Economically important species
  - Fishery species
  - Biofoulers (shipping industry)
- Priority life stages
  - Larval stages for fishes and invertebrates
  - Smolt and juvenile stages (transitional stages)
  - Maternal influences/intergenerational effects
  - Acoustic imprinting
  - Gene expression during development
- Habitat species priorities
  - Estuarine and inlet areas (hydrokinetic power locations and spawning areas for fish)
  - Dark and turbid areas: Is sound more important?
  - Deep sea: Unknown species of sound producers
  - Marine protected areas: Should vessels be limited because of noise?
- Identified challenges
  - More behavioral and physiological studies needed—ecological validity
  - Multispecies interactions (predator/prey)
  - Audiograms: Masking, including particle motion, need joint and independent testing of pressure and particle motion
  - Small tanks are still a problem
  - Behavioral audiograms in situ and auditory evoked potential (AEP): “AEP studies are crap!”—Arthur Popper
  - Behavior may be independent of amplitude: Context very important!
  - Infrasound understudied because difficult to produce with transducers
  - Regulators overextrapolate from results

  - "Gold standard" experiments impossible
  - Difficulty to extrapolate from experiments with transducers if negative results are found
  - Difficulty in communicating negative results in general
  - Many animals continue biological functions during noise (sex, feeding): Plasticity behavior and metabolism may be changing
  - Gene expression
  - Sound metrics (kurtosis and temporal patterns, rise time, dBV good for kurtosis but hard to measure)
  - Sound mapping/distribution mapping: How should regulators apply results?

- Identified solutions
  - Experimental manipulation more possible in fish and invertebrates
  - Translocation experiments
  - Manipulation in natural environment
  - Shaker tables
  - Some lab studies needed too
  - Projectors and internal validity: How to interpret negative results
  - Real sound sources and external validity (both needed)
  - Gold standard is the aim but will progress with incremental steps toward it
  - Very important to write/discuss limitations of studies to prevent regulators overinterpreting
  - Different measures/metrics of sound are relevant in different situations or for different effects.
  - Direct physiological/trauma effects may depend on kurtosis and peak-peak but behavior may not
  - Make use of open source technology to connect more with groups with experience
  - Interdisciplinary collaboration with engineers/physicists
  - Particle motion audiograms: In the field? Laser vibrometry?

5 Summary

Overall, both discussion groups produced several themes and novel concepts for consideration in identifying key baseline biological needs. These outcomes described above should be circulated among conference attendees, their respective organizations, and other interested parties. Furthermore, and perhaps most important, a moderated repository of key data gaps should be pursued at the international level. Such a repository would help develop and maintain a long-term focus on answering key questions rather than the current practice of isolated coordination and potentially overly repetitive research. It would also allow academics and regulators to better connect on key research needs and collaborate on a much greater scale, including time, agency will, and financial resources to meet key needs.

Chapter 162
Summary Report Panel 4: Communication and Interpretation: Presenting Information to the General Public

Gail Scowcroft

Keywords Education • Outreach • Communication

1 Introduction

Complex scientific information is often difficult to communicate to nonscience audiences who may not have the foundational knowledge to understand the content. Scientists are called on with increasing frequency to share the results of their research for the purposes of education, outreach, and popular media stories. These three spheres of activity, represented in Fig. 162.1, are geared toward different but complementary goals.

The sphere of education is likely the most comfortable for scientists because many are required to teach undergraduate and graduate courses in their home institutions. However, their knowledge of science education pedagogy or advancements in the field of learning sciences may be limited. Thus, they may not be as effective as they could be when armed with the knowledge of how people learn. In addition, their exposure to younger students and public audiences may also be limited. Research has shown that the majority of public scientific literacy is acquired outside formal school instruction (Banks et al. 2005).

The sphere of outreach can be foreign territory for scientists. Except for formal proposal writing, most scientists do not get experience or training in fundraising. Nor do they routinely acquire the skills to promote science beyond contributing to the scientific enterprise. Yet, as federal budgets for research shrink, scientists are being called on for more outreach purposes. If citizens understand the need for research and what it can contribute to their well-being or the well-being of other life on Earth, they are more likely to support its funding (Evans and Durant 1995).

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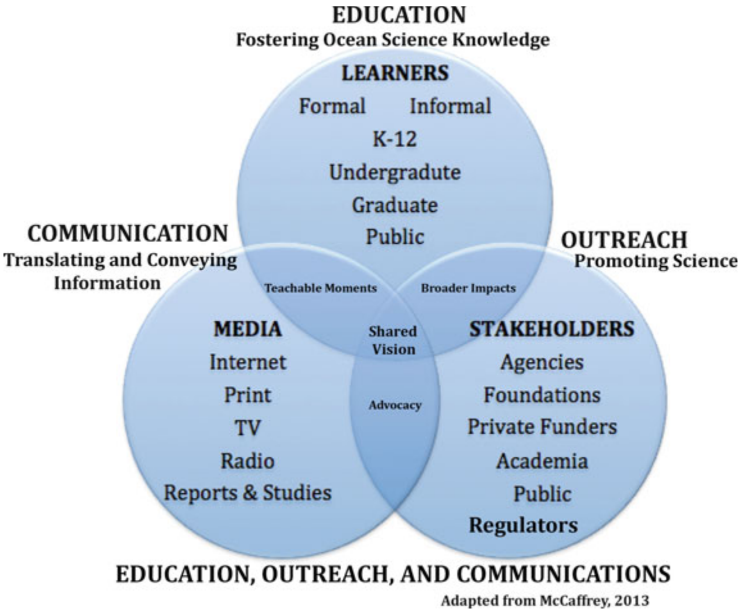

Fig. 162.1 Education, outreach, and communication spheres of activity (Adapted from McCaffery (2013))

2 Education, Outreach, and Communication Activities

Scientists also do not receive training in dealing with the media, yet a large segment of the population gets their knowledge of scientific discoveries from popular media. These science stories may contain incorrect science and, in the worst case, misinformation. Dr. Ben Goldacre, the author of popular books that highlight the publication of "bad science," attributes this miscommunication to the fact that most journalists are humanities graduates without any scientific training (Goldacre 2008). Scientist interactions with the media usually begin with the publication of an important paper in a peer-reviewed journal followed by a press release from their institution, after which they are contacted by a media outlet for an interview. Then they have no control over the final "story" of their work.

Education, outreach, and communication are critical activities for scientists engaged in research related to the effects of sound on aquatic life. This is a topic that is very popular with the public as evidenced by the annual traffic on the *Discovery of Sound in the Sea* Web site (www.dosists.org), which reached close to 13 million "hits" in 2012. Interest is across the globe, with close to 45% of the traffic from outside the United States. So how does the scientific community deal with the demand for their time and this growing public interest?

A panel discussion focused on this topic during the Third International Conference on the Effects of Noise on Aquatic Life. Panelists Dr. Kathleen

Vigness-Raposa, Dr. Marta Picculin, Dr. Paul Thompson, and Ms. Sarika Culis-Sazuki tackled the issues related to education, outreach, and communication of science related to underwater noise. There was a consensus that before engaging in any of these activities, the audience needs to be defined. Potential audiences include colleagues and other scientists; graduate students; undergraduate students; educators; elementary and secondary students; museum, science center, and aquarium audiences; the general public (newspaper readers, TV audiences, and Internet browsers); the media (reporters, writers, and photographers); and policymakers and regulators.

3 Challenges and Strategies

Challenges to successful education, outreach, and communication activities were discussed, with conveying peer-reviewed, technical science to nonscience audiences being the most critical one to overcome. Other challenges include the sensationalism of acoustics issues by the media; misinformation in the press and produced by other stakeholders; the gap between science, uncertainty, and "messages"; increasing public interest; and the lack of control over the accuracy of science in social network postings and Web sites.

Individual scientists can develop successful strategies to meet the above challenges. Each activity should have an identified goal. For example, every reporter does not need to be answered. Before replying, the scientist should ask the question, "Will this story reach my intended audience?" Subsequent questions might be, "Is there an opportunity to deliver a message" and "Can I avoid controversy?"

Each audience requires strategies specific to that audience. For example, a presentation to an undergraduate physics class has very different needs than that to a public aquarium audience. Understanding these differing needs may require training for the scientist or a partnership with an education and/or outreach professional. In the case of education activities, it is important to understand how knowledge is acquired. Collaboration with experts is key to having the broadest and most effective impact possible.

Other successful strategies discussed by the panel members included techniques for engaging a general audience. It is important in any presentation or story to focus on a limited number of take home messages (1–3) that are repeated (beginning, middle, and end). It is also important to deconstruct the science into its key components. Once the goal or message is identified, the scientist should deliver the message from the audience's point of view: what do they want to hear, not what does the scientist want to say. If one determines ahead of time what they want the audience to gain, there will be a greater chance of success. Finally, if data will be displayed, it should be relevant and show causality whenever possible.

A key strategy for communication is for scientists to be involved in the production of press releases related to their own research. It is possible to cultivate relationships with trustworthy journalists. Not all science writers are equally talented.

If an article is well written and accurate, the author can be approached or sent news that a scientist wants published. Following science writers on Twitter, blogs, and other social media is an effective way of finding reliable news outlets. It is important for scientists to be aware of media constraints. Journalists in particular have very quick turnaround times. One option for the modern scientist is to put out his/her own news via blog posts and other social media.

4 Scientist Responsibility

The final topic addressed by the panel was the responsibility of the scientific community. Much of science is funded by public monies. So it is important for the public to be made aware of the results of their investments in research. The communication of results and discoveries needs to be understandable by the public. Scientists are a small percentage of the population; if support for research and scientific literacy is to be achieved, the public must be engaged. Scientists also have a responsibility for communicating uncertainty. This is a concept not understood by the public, who often are seeking concrete, definitive answers to questions, when research results can only provide the range of possibilities. Science can be accurate, but often the "story" may not be able to be complete.

The modern scientist is called on to be much more than just a researcher. He or she is an ambassador of science and, as such, needs the appropriate training and support. Graduate science programs are adding the communication of science and teaching skills to their curricula. As the next generation of scientists enters the field, there is hope that significant progress can be made in the public understanding of science.

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