Chapter 13
Passive Acoustic Monitoring in Benthic Marine Crustaceans: A New Research Frontier

Erica Staaterman

Abstract Passive acoustic monitoring has been used to study the soundscapes of some shallow-water coastal environments. These studies have revealed distinct patterns that depend upon the physical structure of the environment as well as the species living within it. One underrepresented group in marine bioacoustics is the benthic crustaceans, yet these animals are known to produce and detect sounds. Snapping shrimp are the most ubiquitous benthic crustacean, and their "snaps" can substantially elevate sound levels in the range of 2–15 kHz in a variety of habitats in the mid-latitudes. Clawed and spiny lobsters produce tonal vibrations and broadband "rasps," respectively, but these sounds occur more intermittently than the snapping shrimp choruses. Finally, burrow-dwelling mantis shrimp produce low-frequency rhythmic "rumbles" which tend to occur as dawn and dusk choruses. Passive acoustic monitoring of these taxa can be useful for revealing broad ecological patterns, by using some species (e.g., snapping shrimp) as ecological indicators. Acoustic measurements can reveal temporal patterns in crustacean sounds and detect species' occupancy of particular habitats. Finally, acoustic monitoring can demonstrate the temporal and frequency overlap between anthropogenic sounds and natural crustacean sounds, which can help refine research questions on potential impacts.

13.1 Introduction

Passive acoustic monitoring (PAM) is a promising new field of research, which can uncover both broad and fine-scale ecological patterns. For example, through new types of complexity indices, entire communities can be surveyed and compared acoustically (Sueur et al. 2008; Gasc et al. 2013). On the fine scale, temporal patterns in the natural acoustic behaviors of specific organisms, as well as their response

---

E. Staaterman (✉)
Smithsonian Environmental Research Center, Smithsonian Institution,
647 Contees Wharf Road, Edgewater, MD, USA

Beneath the Waves, Inc., Syracuse, NY, USA
e-mail: e.staaterman@gmail.com

W.W.L. Au, M.O. Lammers (eds.), *Listening in the Ocean*, Modern Acoustics
and Signal Processing, DOI 10.1007/978-1-4939-3176-7_13

to disturbance events, can be investigated using passive acoustics (e.g., Locascio and Mann 2005, 2008). Through acoustic recordings, investigators have found that specific benthic habitats have unique sound signatures (Radford et al. 2010; McWilliam and Hawkins 2013). Although much variation in underwater soundscapes may be due to abiotic sound sources (Wenz 1962), the contribution of the biophony to benthic soundscapes, and the site-specific differences within these environments, merits further investigation. Here we provide an overview of the research on benthic soundscapes, with a particular focus on bioacoustic studies of benthic crustaceans.

Although historically much research on ocean noise has focused on deep-water areas, several shallow-water, coastal environments have been explored acoustically, and each has revealed exciting results. For example, Radford et al. (2010) measured soundscapes off of the coast of New Zealand on a macroalgal-dominated rocky reef, a sandy bottom, and an urchin-dominated rocky reef. They found distinct acoustic signatures from all three sites, with a specific acoustic contribution from the sea urchins (Radford et al. 2008, 2010). More recently, McWilliam and Hawkins (2013) found that within an Irish Lough, a cliff site, a gravel site, and a mud site had distinct spectra, which was likely explained by a combination of different sediment characteristics and biological composition. Finally, oyster reefs and nearby soft-bottom habitats within the same estuary also showed unique sound spectra (Lillis et al. 2013). Even the sounds produced by bivalves (so-called "coughs") have recently been identified, which may provide yet another unique sound to monitor (Di Iorio et al. 2012). These studies highlight the fact that the presence of certain benthic marine organisms can influence a marine soundscapes in several ways: by physically changing habitat structure (e.g., the presence of an oyster reef or macroalgae), and also by contributing to the unique biophony of that habitat. These descriptive studies provide valuable baseline data for marine habitats, but do not necessarily target specific sound-producers. However, because PAM allows investigators the opportunity to "spy" on their study species, it can be used to learn about natural acoustic behaviors of soniferous benthic organisms such as crustaceans.

13.2 Decapod Crustacean Sounds

While sound production in crustaceans has been documented for centuries (Wood Mason 1878), it was not until recently that investigators began to use PAM to study these species. Laboratory studies have identified various types of crustacean sounds (e.g., Hazlett and Winn 1962; Meyer-Rochow and Penrose 1976; Patek and Caldwell 2006), sound production mechanisms (e.g., Ritzmann 1973; Imafuku and Ikeda 1990; Patek 2002) and neurological receivers and sensitivity (e.g., Salmon and Horch 1976; Goodall et al. 1990). Crustaceans are indeed capable of detecting acoustic signals: sensory hairs on the exoskeleton are sensitive to substrate-borne or water-borne vibrations (Goodall et al. 1990; Tautz 1990; Budelmann 1992; Popper et al. 2001). In addition, crustaceans can detect particle motion and possibly acoustic pressure through chordotonal organs on their joints and statocyst detectors at the base of the antennae (Breithaupt and Tautz 1988; Budelmann 1992; Popper et al. 2001; Taylor and Patek 2010). Clearly these animals are acoustically active, and there is a need to better understand the behavioral functions of sounds, which can best be explored in the field.

The most ubiquitous and well-studied sounds produced by crustaceans are the characteristic "snaps" of the snapping shrimp. The acoustic behaviors and characteristics of these sounds were first described by Johnson et al. (1947). They identified that these soniferous benthic crustaceans can live in habitats ranging from eelgrass to rocky reefs to coral reefs, and are dominant in the mid-latitudes (Johnson et al. 1947). Snapping shrimp sound levels, which are strongest in the range of 2–15 kHz, are typically higher at night than during the day, with a peak during dawn and dusk (Johnson et al. 1947). Tank experiments by Hazlett and Winn (1962) attempted to determine the behavioral trigger for the alpheid shrimp's "snap," and found that it is used in a territorial context (Hazlett and Winn 1962). Some field work has attempted to count individual "snaps" as an ecological indicator tool, but the authors caution that this method may only be applicable within specific locations, rather than between sites (Watanabe et al. 2002). Because snapping shrimp are common on coral reefs, these sounds have received attention in studies on coral reef soundscapes and may indeed be correlated with certain measures of ecological health (Lammers et al. 2008; Kennedy et al. 2010; Staaterman et al. 2013). However, because snapping shrimp can also inhabit rocky reefs and even coral rubble (Enochs et al. 2011), a high level of snapping shrimp noise does not necessarily reflect a large percentage of live coral. In the future, PAM work should be combined with careful benthic surveys to better assess the relationship between snapping shrimp sounds and life on the reef.

While not as ubiquitous as snapping shrimp, lobsters, too, produce sounds. Henninger and Watson (2005) revealed the physiological mechanism responsible for the tonal, low-frequency vibrations produced by clawed lobsters, but did not determine the behavioral significance (Henninger and Watson III, 2005). Sound production in several species of spiny lobsters has been well studied; these lobsters produce a broadband "rasp" through a stick-and-slip mechanism (Patek 2002). To determine the behavioral context of rasps in California spiny lobsters, Staaterman et al. (2009) presented *Panulirus interruptus* individuals with different model aggressors and noticed that they only responded acoustically after they had been physically contacted, suggesting that the "rasp" serves as an antipredator startle signal (Staaterman et al. 2009). The use of passive acoustic monitoring in this environment would allow researchers to understand natural predator–prey interactions by recording the occurrence of these antipredator sounds. Furthermore, sounds that are produced as a byproduct of lobster movement, especially during their active nocturnal foraging period, may be evident through long-term recordings and could be used to monitor the presence or absence of this species. Mulligan and Fischer (1977) found that the sister species, the Caribbean spiny lobster *P. argus*, produces three types of sounds: "flutter," "popping," and "rasp," depending on the level of arousal (Mulligan and Fischer 1977). Hazlett and Winn (1962) examined natural diel variation in *P. argus* sounds through passive recordings on a reef in Bermuda

(Hazlett and Winn 1962). They found that more sounds were produced at night, but acknowledged the limitations of their conclusions due to low replication. They were only able to make three recordings, spread across 2 years and two different months, presumably due to technical limitations (Hazlett and Winn 1962). This is precisely the type of experimental question that can be revisited with passive acoustic monitoring, now that tools are available for longer-term recordings.

13.3 Stomatopod Crustacean Sounds

In addition to decapod crustaceans, stomatopod crustaceans are known to produce sounds as well. The mantis shrimp strike produces a sound that is similar to the snapping shrimp "snap," but is a by-product of feeding and aggressive behaviors (Hazlett and Winn 1962; Caldwell 1979; Patek and Caldwell 2005). In addition to the strike sound, at least one species of mantis shrimp, *Hemisquilla californiensis*, is known to produce a sound that is not associated with strike behavior: a low-frequency "rumble," first recorded in tanks by Patek and Caldwell (2006). The authors recorded sounds from males while held in tanks, and through dissections they deduced that rumbles are produced by a pair of muscles under the carapace.

When a species' sounds have already been characterized in a lab setting, passive acoustic monitoring is the logical next step for understanding its acoustic ecology. A follow-up study by Staaterman et al. (2011) explored the temporal patterns of sound production in the California mantis shrimp through PAM. The investigators deployed an autonomous recording unit in the habitat of *H. californiensis*, near a mantis shrimp burrow, for 8 days during the mating season. They found that there were distinct daily patterns in mantis shrimp acoustic activity (Table 13.1). During crepuscular periods, the rumbles were loud and highly rhythmic. Multiple mantis shrimp were often audible during these times, creating a "mantis shrimp chorus." The authors noted that these acoustic patterns matched known patterns of physical activity—mantis shrimp are most active during crepuscular periods, typically seen foraging or guarding the entrance to their burrows (Basch and Engle 1989). Because the recordings were made during the mating season, they hypothesized that the rumbles could be used by males to attract females or to defend their burrows. This chorusing behavior is analogous to observations in many terrestrial animals (Bradbury and Vehrencamp 1998). During the nighttime, the authors recorded sounds that resembled mantis shrimp rumbles but were quieter and less rhythmic (Table 13.1) (Staaterman et al. 2011). They suggested that these sounds could have been produced while mantis shrimp were deep inside their burrows, further from the hydrophone. Recording the sounds of *H. californiensis* during an 8-day period allowed the investigators to discern daily acoustic patterns and match them to previously published behavioral observations (Basch and Engle 1989), and to propose hypotheses about the function of the rumbles. These ideas would not have been possible without the ability to listen continuously to the mantis shrimp habitat.

Table 13.1 Daily patterns in the acoustic activity of the California mantis shrimp (*Hemisquilla californiensis*) were consistent with published data on behavioral activity and burrow openings (fifth column in table below corresponds to data from Fig. 13.3 in Basch and Engle (1989), $n = 13$ individuals)

Time of day	Approximate hours	Acoustic activity observed	Number of days observed	Percentage of burrows open
Morning Crepuscular period	~06:30–08:30 h	Loud, rhythmic rumbles	8 out of 8 days	50 % of burrows open
Mid-morning	~9:30–11:30 h	Loud, rhythmic rumbles	6 out of 8 days	Not documented
Mid-day	~11:30–01:30 h	No rumbling	6 out of 7 days	15 % of burrows open
Evening crepuscular period	~17:00–19:30 h	Loud, rhythmic rumbles	7 out of 8 days	50–70 % of burrows open
Night	~20:00–05:30 h	Quiet, sporadic, lower frequency rumbles	8 out of 8 days	0 % of burrows open

Sounds were recorded for almost 8 continuous days, but one midday period was missed. Table reproduced from Staaterman et al. (2011)

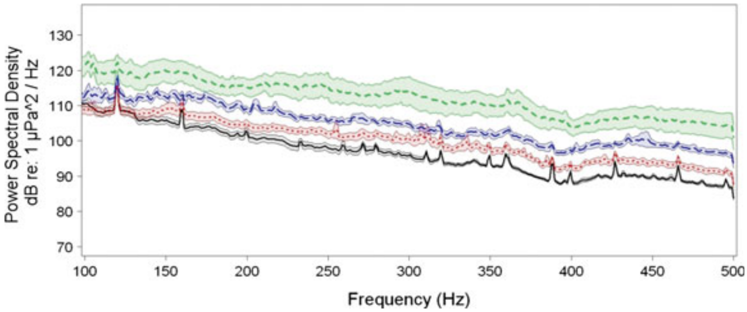

Fig. 13.1 The average of sound levels from different times of day, recorded at Catalina Island, CA, demonstrated that midday periods were significantly louder than the other times of day due to vessel traffic. Power spectral density (± standard error, dB re: 1 $\mu Pa^2\ Hz^{-1}$) is shown as a function of frequency (Hz) for each 1-h period. *Green*: 12:00–13:00 h; *blue*: 18:00–19:00 h; *red*: 06:00–07:00 h; *black*: 00:00–01:00 h. Peaks at 120 and 160 Hz were created by the perpetual "hum" from the autonomous recording unit (Staaterman et al. 2011 and unpublished data)

In further examination of the data, the same authors also measured variation in daily noise levels across the mantis shrimp bandwidth, to examine the prevalence of boat noise (Staaterman et al. 2012 and unpublished data). They examined 1-h sound files for representative times of day: 0:00–1:00 h, 6:00–7:00 h, 12:00–13:00 h, and 18:00–19:00 h and found that midday periods were significantly louder than the others, primarily due to boat traffic (Fig. 13.1).

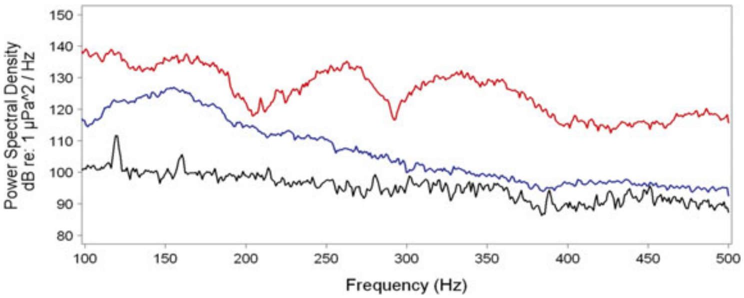

Fig. 13.2 Vessel noise (*red line*) power spectral density measurements (dB re: 1 µPa^2 Hz^{-1}) were significantly greater than mantis shrimp rumbles (*blue line*) and background noise (*black line*) across all frequencies (Hz). Peaks at 120 and 160 Hz were created by the perpetual "hum" from the autonomous recording unit's hard drive (Staaterman et al. 2011 and unpublished data)

They also measured the intensity level of each of these sources (Staaterman et al., unpublished data), and found that each source was distinct in frequency distribution and intensity characteristics (Fig. 13.2), particularly in the 100–250 Hz frequency band, which is the communication bandwidth of the mantis shrimp. On average, the contribution of vessel noise was 12 dB greater than that from mantis shrimp rumbles and 30 dB greater than the background noise (Fig. 13.2).

Finally, 24 hour spectrograms revealed that noise from boat traffic was frequent, especially during the daytime hours (Fig. 13.3, Staaterman et al., unpublished data). Boat noise was significantly louder than mantis shrimp rumbles and is clearly capable of masking these sounds (Figs. 13.2 and 13.3). This is one example of how PAM can be used to examine patterns, and potential overlap, between biological and anthropogenic sound sources within one acoustic habitat.

Although the use of PAM has been limited thus far for benthic crustaceans, this method holds great promise for this extremely diverse taxonomic group. In fact, PAM may be most useful for benthic animals such as burrowing shrimp or crabs, since they are relatively sedentary. For animals that are most active at night, such as spiny lobsters, active acoustic experiments in the field are extremely difficult. But passive acoustic monitoring may be able to reveal not only their movement patterns, but also feeding activity and predator–prey interactions. Finally, the deployment of acoustic recorders at multiple locations within and between habitats may help scientists to understand the spatial distribution of acoustically active crustaceans. Considering how little we know about the acoustic ecology of crustaceans, this type of research will inevitably be novel and exciting, a frontier waiting to be explored.

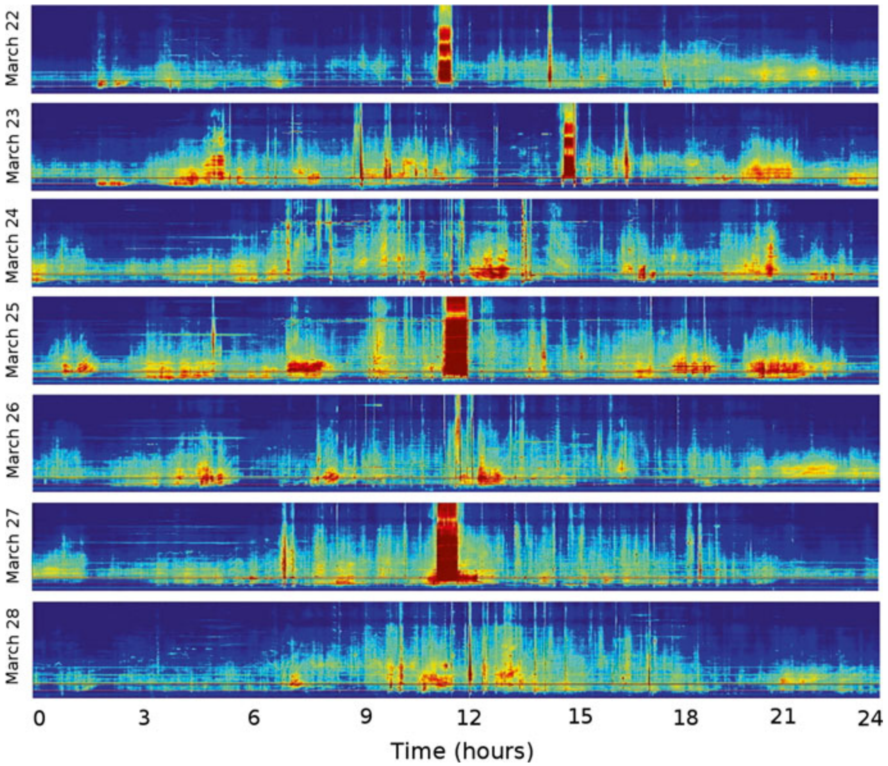

Fig. 13.3 Twenty-four hour spectrograms (0–500 Hz on *y*-axis, color scale: relative dB) from Catalina Island, CA, in March 2009 illustrate temporal patterns in the acoustic habitat of the California mantis shrimp. Note the frequent and high intensity broadband *vertical lines*, especially during daylight hours, which represent vessel noise. The *horizontal lines* were a result of the unit's hard drive (Staaterman et al. 2011 and unpublished data)

References

L.V. Basch, J.M. Engle, Aspects of the ecology and behavior of the stomatopod Hemisquilla ensigera californiensis (Gonodactyloidea: Hemisquillidae), in *Biology of Stomatopods*, ed. by E.A. Ferrero (Mucchi, Modena, 1989)

J.W. Bradbury, S.L. Vehrencamp, *Principles of Animal Communication* (Sinauer Associates, Sunderland, MA, 1998)

T. Breithaupt, J. Tautz, Vibration sensitivity of the crayfish statocyst. Naturwissenschaften **75**, 310–312 (1988)

B.U. Budelmann, Hearing in Crustacea", in *The Evolutionary Biology of Hearing*, ed. by D.B. Webster, R.R. Fay, A.N. Popper (Springer, New York, MA, 1992), pp. 131–139

R.L. Caldwell, Cavity occupation and defensive behaviour in the stomatopod *Gonodactylus festae*: evidence for chemically mediated individual recognition. Anim. Behav. **27**, 194–201 (1979)

L. Di Iorio, C. Gervaise, V. Jaud, A.A. Robson, L. Chauvaud, Hydrophone detects cracking sounds: non-intrusive monitoring of bivalve movement. J. Exp. Mar. Biol. Ecol. **432–433**, 9–16 (2012)

I.C. Enochs, L.T. Toth, V.W. Brandtneris, J.C. Afflerbach, D.P. Manzello, Environmental determinants of motile cryptofauna on an eastern Pacific coral reef. Mar. Ecol. Prog. Ser. **438**, 105–118 (2011)

A. Gasc, J. Sueur, F. Jiguet, V. Devictor, P. Grandcolas, C. Burrow, M. Depraetere, S. Pavoine, Assessing biodiversity with sound: do acoustic diversity indices reflect phylogenetic and functional diversities of bird communities? Ecol. Indic. **25**, 279–287 (2013)

C. Goodall, C. Chapman, D. Neil, The acoustic response threshold of the Norway lobster, *Nephrops norvegicus* (L.) in a free sound field, in *Frontiers in Crustacean Neurobiology*, ed. by K. Wiese, W.D. Krenz, J. Tautz, H. Reichert (Birkhauser Verlag, Boston, MA, 1990), pp. 106–113

B.A. Hazlett, H.E. Winn, Sound production and associated behavior of Bermuda crustaceans (Palinurus, Gonodactylus, Alpheus, Synalpheus). Crustaceana **4**, 25–38 (1962)

H.P. Henninger, W.H. Watson III, Mechanisms underlying the production of carapace vibrations and associated waterborne sounds in the American lobster, *Homarus americanus*. J. Exp. Biol. **208**, 3421–3429 (2005)

M. Imafuku, H. Ikeda, Sound production in the land hermit crab *Coenobita purpureus* Stimpson, 1858 (Decapoda, Coenobitidae). Crustaceana **58**, 168–174 (1990)

M.W. Johnson, F.A. Everest, R.W. Young, The role of snapping shrimp (Crangon and Synalpheus) in the production of underwater noise in the sea. Biol. Bull. **93**, 122–138 (1947)

E.V. Kennedy, M.W. Holderied, J.M. Mair, H.M. Guzman, S.D. Simpson, Spatial patterns in reef-generated noise relate to habitats and communities: evidence from a Panamanian case study. J. Exp. Mar. Biol. Ecol. **395**, 85–92 (2010)

M.O. Lammers, R.E. Brainard, W.W. Au, T.A. Mooney, K.B. Wong, An ecological acoustic recorder (EAR) for long-term monitoring of biological and anthropogenic sounds on coral reefs and other marine habitats. J. Acoust. Soc. Am. **123**, 1720–1728 (2008)

A. Lillis, D.B. Eggleston, D.R. Bohnenstiehl, Oyster Larvae Settle in response to habitat-associated underwater sounds. PLoS One **8**, 79337 (2013)

J.V. Locascio, D.A. Mann, Effects of hurricane Charley on fish chorusing. Biol. Lett. **1**, 362–365 (2005)

J.V. Locascio, D.A. Mann, Diel periodicity of fish sound production in Charlotte Harbor, Florida. Trans. Am. Fish. Soc. **137**, 606–615 (2008)

J.N. McWilliam, A.D. Hawkins, A comparison of inshore marine soundscapes. J. Exp. Mar. Biol. Ecol. **446**, 166–176 (2013)

V.B. Meyer-Rochow, J.D. Penrose, Sound production by western rock lobster *Panulirus longipes* (Milne-Edwards). J. Exp. Mar. Biol. Ecol. **23**, 191–209 (1976)

B.E. Mulligan, R.B. Fischer, Sounds and behavior of spiny lobster *Panulirus argus* (Latreille, 1804) (Decapoda, Palinuridae). Crustaceana **32**, 185–199 (1977)

S. Patek, Squeaking with a sliding joint: mechanics and motor control of sound production in palinurid lobsters. J. Exp. Biol. **205**, 2375–2385 (2002)

S.N. Patek, R.L. Caldwell, Extreme impact and cavitation forces of a biological hammer: strike forces of the peacock mantis shrimp (*Odontodactylus scyllarus*). J. Exp. Biol. **208**, 3655–3664 (2005)

S.N. Patek, R.L. Caldwell, The stomatopod rumble: Low frequency sound production in *Hemisquilla californiensis*. Mar. Freshw. Behav. Physiol. **39**, 99–111 (2006)

A.N. Popper, M. Salmon, K.W. Horch, Acoustic detection and communication by decapod crustaceans. J. Comp. Physiol. A **187**, 83–89 (2001)

C. Radford, A. Jeffs, C. Tindle, J.C. Montgomery, Resonating sea urchin skeletons create coastal choruses. Mar. Ecol. Prog. Ser. **362**, 37–43 (2008)

C.A. Radford, J.A. Stanley, C.T. Tindle, J.C. Montgomery, A.G. Jeffs, Localised coastal habitats have distinct underwater signatures. Mar. Ecol. Prog. Ser. **401**, 21–29 (2010)

R. Ritzmann, Snapping behavior of the shrimp *Alpheus californiensis*. Science **181**, 459–460 (1973)

M. Salmon, K. Horch, Acoustic interneurons of fiddler and ghost crabs. Physiol. Zool. **49**, 214–226 (1976)

E.R. Staaterman, T. Claverie, S.N. Patek, Disentangling defense: the function of spiny lobster sounds. Behaviour **147**, 235–258 (2009)

E.R. Staaterman, C.W. Clark, A.J. Gallagher, M.S. DeVries, T. Claverie, S.N. Patek, Rumbling in the benthos: acoustic ecology of the California mantis shrimp *Hemisquilla californiensis*. Aquat. Biol. **13**, 97–105 (2011)

E.R. Staaterman, C.W. Clark, A. Gallagher, T. Claverie, M. DeVries, S.N. Patek, Acoustic Ecology of the California Mantis Shrimp, in *The Effects of Noise on Aquatic Life*, ed. by A.N. Popper, A. Hawkins (Springer New York, New York, NY, 2012), pp. 165–168

E. Staaterman, A.N. Rice, D.A. Mann, C.B. Paris, Soundscapes from a tropical Eastern Pacific reef and a Caribbean Sea reef. Coral Reefs **32**, 553–557 (2013)

J. Sueur, S. Pavoine, O. Hamerlynck, S. Duvail, Rapid acoustic survey for biodiversity appraisal. PLoS One **3**, 4065 (2008)

J. Tautz, Coding of mechanical stiumuli in crustaceans – what and why? in *Frontiers in Crustacean Neurobiology*, ed. by K. Wiege, W.D. Krenz, J. Tautz, H. Reichest, B. Mulloneg (Birkhauser Verlag, Basel, 1990), pp. 200–206

J.R.A. Taylor, S.N. Patek, Crustacean seismic communication: heard but not present?", in *The Use of Vibrations in Communication: Properties. Mechanisms and Function Across Taxa*, ed. by C.E. O'Connell-Rodwell (Research Signpost, Kerala, 2010), pp. 9–23

M. Watanabe, M. Sekine, E. Hamada, M. Ukita, T. Imai, Monitoring of shallow sea environment by using snapping shrimps. Water Sci. Technol. **46**, 419–424 (2002)

G.M. Wenz, Acoustic ambient noise in the ocean: spectra and sources. J. Acoust. Soc. Am. **34**, 1936–1956 (1962)

J. Wood Mason, Stridulating crustaceans. Nature **18**, 53 (1878)