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Shark attraction using a video-acoustic system

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Abstract

An underwater television system located off Bimini, Bahamas, was used to observe and record the attraction of free-ranging sharks to a nearby sound source. Several species of sharks were attracted by irregularly pulsed signals either containing harmonics (e.g., overdriven sine waves) or consisting of octave bands of noise. Irregularly pulsed, pure tones and harmonic sounds above 1000 Hz were apparently not attractive. Attraction was not reinforced, and habituation of the approach response was regularly observed in prolonged test series. As the number of sharks in the test area increased, swimming activity rose dramatically. Circling and criss-crossing of the site became more intense under conditions of low ambient light and turbidity. Additional tests showed that minimum attractive sound levels were remarkably low, and that sharks could locate a sound source within seconds from distances beyond our limit of visibility (about 25 m).

Introduction

Various factors have limited progress in our understanding of the behavioral activities of marine fauna. Two, in particular, appear outstanding.

The first is simply that many good observers and experimentalists are not willing, nor able, to dive. Students of behavior have used mask and snorkel, SCUBA, and even hard hat diving gear in the field; but depth restrictions of present day diving, dependence upon a breathing apparatus, and the unaccustomed limitations of our senses to warn us of dangerous situations have deterred many *in situ* studies.

The second factor is the lack of detail that has often accompanied behavioral studies carried out under field conditions. Only within the last few years have sufficient advances been made in observational, experimental, and analytical techniques to permit a significant increase in understanding and, in certain cases, prediction and control of animal behavior under natural conditions. Such achievements are rare, however, when research requires direct, yet detailed, observation and experimentation in the ocean at depths of over 1 or 2 m. The relatively short duration of a dive, for example, often prevents sufficient observation for detailed time series analyses. The unavoidable presence of a diver at his study area is another consideration. Slight disturbances may well be unimportant, but necessary rapid approaches and departures from a study area, release of exhaust bubbles, and movements resulting from current and/or surge effects, sometimes stretch the idea of the quiet, hidden observer beyond a reasonable limit.

Strong emphasis has been directed at reducing the above limitations by renewed interest in submersibles (Piccard, 1966; Hull, 1967; Rechnitzer, 1967; Rebikoff, 1967). Their various sizes, speeds, and depth capabilities certainly afford distinct advantages over diving. On the other hand, their size, noise, restricted viewing, logistical support, and costs, often preclude their use in many behavior studies.

A second development is that of closed circuit underwater television (UTV). Initially, UTV systems were operated from ships, but recently they have become independent of such a moving platform (Kumpf and Lowenstein, 1962; Barnes, 1963; Steinberg and Koczy, 1964; La Fond, 1965; Booda, 1966). One concept has been to operate and control underwater surveillance by remote UTV from a land-based laboratory (Galler and Wallen, 1967). The underwater portion of the system, i.e., camera, pan, tilt, and zoom components, is contained in a relatively small, waterproof housing; the latter is set on the bottom in a desired area, and there it remains, if necessary, for months at a time.

Bimini video-acoustic system

Such an installation, along with associated underwater acoustic equipment, has been developed by scientists from the Institute of Marine Sciences, University of Miami, under the auspices of the Oceanic Biology Program, Office of Naval Research, and in cooperation with the Lerner Marine Laboratory of the American Museum of Natural History. The underwater system (Fig. 1) operates at a depth of 20 m, 1.5 km off the west coast of North Bimini, near the eastern edge of the Gulf Stream (Fig. 2) (Myrberg et al., 1966; Stevenson, 1967; Holt, 1967; Editorial Notes and News, 1967). The underwater scene is monitored on a screen in the laboratory and, when desirable, the scene, as well as the sounds picked up by associated hydrophones, is recorded on magnetic video and/or sound tape (Kronengold et al., 1964). The camera housing is 1 m high and 0.5 m in diameter. Internal pan and tilt mechanisms allow 360° horizontal, and 50° vertical views, while a zoom lens (17 to 70 mm) permits close-up to wide angle viewing.

One purpose of the Bimini system has been to demonstrate its usefulness as a tool in marine biological research, and specifically as an aid in unraveling important relationships between behavioral activities of free-living animals and acoustical phenomena (Cummings et al., 1964; Kumpf, 1964). To fulfill this purpose, various investigations have been carried out. One of these is the subject of this report. We bring it forth here, since it not only demonstrates the usefulness of a video-acoustic system as a tool for *in situ* studies, but it deals also with a subject about which knowledge is meager — shark behavior.

Fig. 1. Underwater television camera housing, located 1.5 km off the west coast of North Bimini, Bahamas, at a depth of 20 m (Photo by E. FISHER)

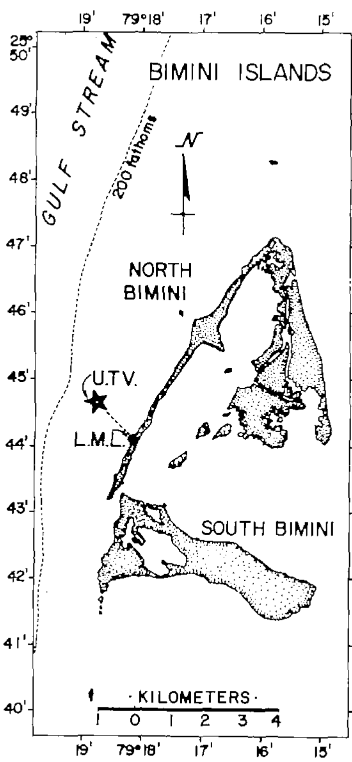

Fig. 2. The Bimini Islands, Bahamas. U.T.V.: underwater site of the UTV system; L.M.L.: Lerner Marine Laboratory; dotted line shows path of control cables

An interest in bio-acoustics, coupled with a program of shark research, resulted in a series of field experiments aimed at answering, or at least clarifying, various questions that have been posed regarding the effects of acoustic signals upon the behavior of free-ranging sharks.

Background for acoustic study

It would seem, on an *a priori* basis, that sound might well be an important stimulus for controlling certain activities of sharks. Water is a far better sound conductor than air; sound velocity approaches a speed of 1600 m/sec in seawater compared to about 350 m/sec in air. Additionally, attenuation is lower in water than in air. Sensitive hearing might, therefore, provide a predator with an excellent means of detecting, recognizing, and localizing it's prey over considerable distance.

On the other hand, other modalities used by terrestrial animals for obtaining information about distant sources are somewhat handicapped underwater. The visual range, for example, is probably reduced to only a few meters for marine animals; even the clear waters off Bimini provided transparency roughly equivalent to a moderately heavy fog on land. In turbid waters, vision may become, to all intents and purposes, useless. The chemical senses are often similarly handicapped because of the slow diffusion rates in water and the complications that can occur by the effects of current, surge, and eddies.

What little knowledge we have about the behavior of free-ranging sharks stems largely from 2 sources. The first has been encounters between man and free-ranging sharks (e.g. WRIGHT, 1948; HAAS, 1957; EIBL-EIBESFELDT and HAAS, 1959; LLANO, 1963; COPPLESON, 1963). Many of these have strongly indicated that sound is an important stimulus, resulting in the arrival of sharks and, in some cases, subsequent attack. Sound, in this context, refers to those mechanical disturbances propagated in an elastic medium, included are both pressure variations and particle displacements in the medium.

Our second source of knowledge comes from studies carried out in large enclosures of various research laboratories (e.g. KRITZLER and WOOD, 1961; DAVIES et al., 1963a; TESTER and KATO, 1966). These studies have concerned themselves largely with physiological capabilities and, unfortunately, they often shed little light on the use of such capabilities under natural conditions. Yet, such investigations are important for behavioral studies, since they indicate the various types of environmental information available to a given species.

Hearing capabilities have been studied in a few sharks. Detailed information is available for the bull shark *Carcharhinus leucas* (KRITZLER and WOOD, 1961) and the lemon shark *Negaprion brevirostris* (NELSON, 1967a). General information is available for the dogfishes *Mustelus canis* (PARKER, 1909) and *Squalus acanthias* (VILSTRUP, 1951); the hammerhead *Sphyrna lewini* (OLLA, 1962); the dusky *C. obscurus* and the spinner *C. maculipinnis* (DAVIES et al., 1963b). In view of the findings of the above studies, it is reasonable to assume that sharks, as a group, are sensitive to low and medium frequency acoustic signals, with rapidly decreasing sensitivity above 1500 Hz.

Evidence of sound localization has been reported in several of the above species of sharks tested in enclosures, while field data have also pointed to the same ability (NELSON, 1967b; NELSON and GRUBER, 1963). Some workers have maintained, however, that such studies have supplied evidence of directional hearing only within the acoustic near-field; and that evidence is still lacking as to such ability in the acoustic far-field (p. 271). Also, several classes of sound have been ineffective in attracting free-ranging sharks (HOBSON, 1963; WISBY et al., 1964). Therefore, reasonable doubt still surrounds this question and a definitive investigation might clarify this issue.

Based upon the above considerations, an investigation was undertaken, using the Bimini Video-Acoustic Installation, to determine whether groups of free-ranging sharks could be attracted by acoustic signals. If attraction was established beyond doubt, attempts would then be made at determining: 1) differences in the attractive nature of various types of acoustic signals, 2) shark identifications, 3) possible habituation to acoustic signals in the absence of apparent positive reinforcement, 4) the upper frequency limit for purposes of attracting sharks, and 5) hearing and directional orientation to a sound source by sharks in the acoustic far-field.

Instrumentation and experimental design

Fig. 3 presents a schematic of the UTV site, including the location of the underwater equipment. Signals were transmitted by a sound projector, positioned 3 m from the UTV and 1 m above the bottom, resting on a pad of rubberized horsehair. Signal control was maintained from the laboratory.

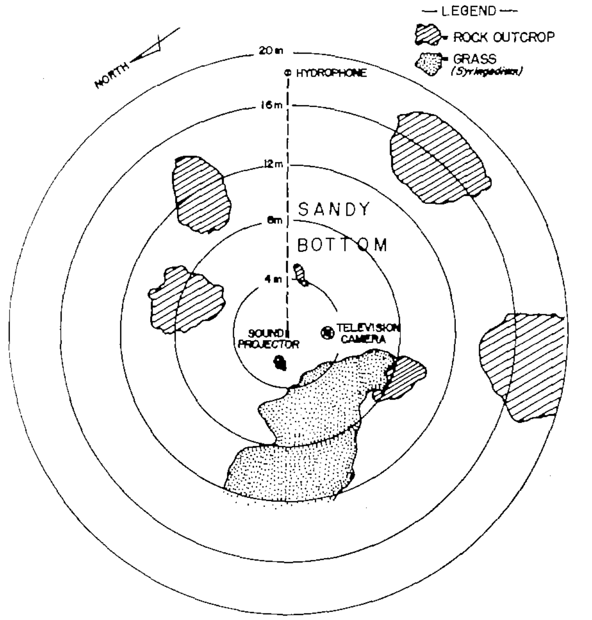

Fig. 3. Bottom terrain at the Bimini UTV site, showing the location of the television camera, sound projector, and hydrophone

Audio-equipment included a hydrophone and preamplifier (model 2Z110, Hudson Laboratories), broad-band sound projector (model J-9, Chesapeake Instrument Corp.), random noise generator (type 811-B, H. H. Scott, Inc.) audio-oscillator (model 200 CD, Hewlett-Packard), band-pass filter (model 330-M, Krohn-Hite), and an audio amplifier (model T50, Allen Organ Co.).

Sound waves, generated by the projector, as well as ambient noise, were received by the calibrated pressure hydrophone, positioned 18.5 m from the projector. Voltmeters, and tape-recorders were used for monitoring. The variable, band-pass filter was used in determining signal-to-noise relationships and to control frequency cut-off of selected random noise signals.

The viewing range of the UTV varied somewhat during the investigation because of changes in turbidity and ambient light level, but sufficient clarity for purposes of testing was afforded all periods of observation.

Sine wave signals, originating from the audio-oscillator, passed directly to the amplifier used to drive the projector. By either overdriving the power amplifier or by using it within its normal range, 2 classes of signals were produced — pure and "overdriven" sine waves. The latter resulted in odd-harmonic, biphasic, square waves (Fig. 4). Broad-band sounds formed a third class. These signals were produced with the white-noise generator and passed successively through the band-pass filter and a transient-less photoswitch, before entering the driving amplifier. All signals were monitored at the amplifier output by an oscilloscope and voltmeter.

Sound levels of "overdriven" signals were maintained slightly more than 20 dB above the level of broad-band ambient noise at the hydrophone. All other signals (except tests 2 and 3 of the Far-Field Series, Table 3) were maintained slightly less than 20 dB above this broad-band level. Spectrum levels of representative test signals are shown in Fig. 5.

All signals were pulsed rapidly and irregularly by manually keying the system. The number of pulses per sec, and their duration, varied, based upon the dexterity of the operator. Pulse intervals varied from about 0.05 sec to 1 sec, while the pulse duration varied from 0.05 sec to 2 sec (Figs. 4 and 10).

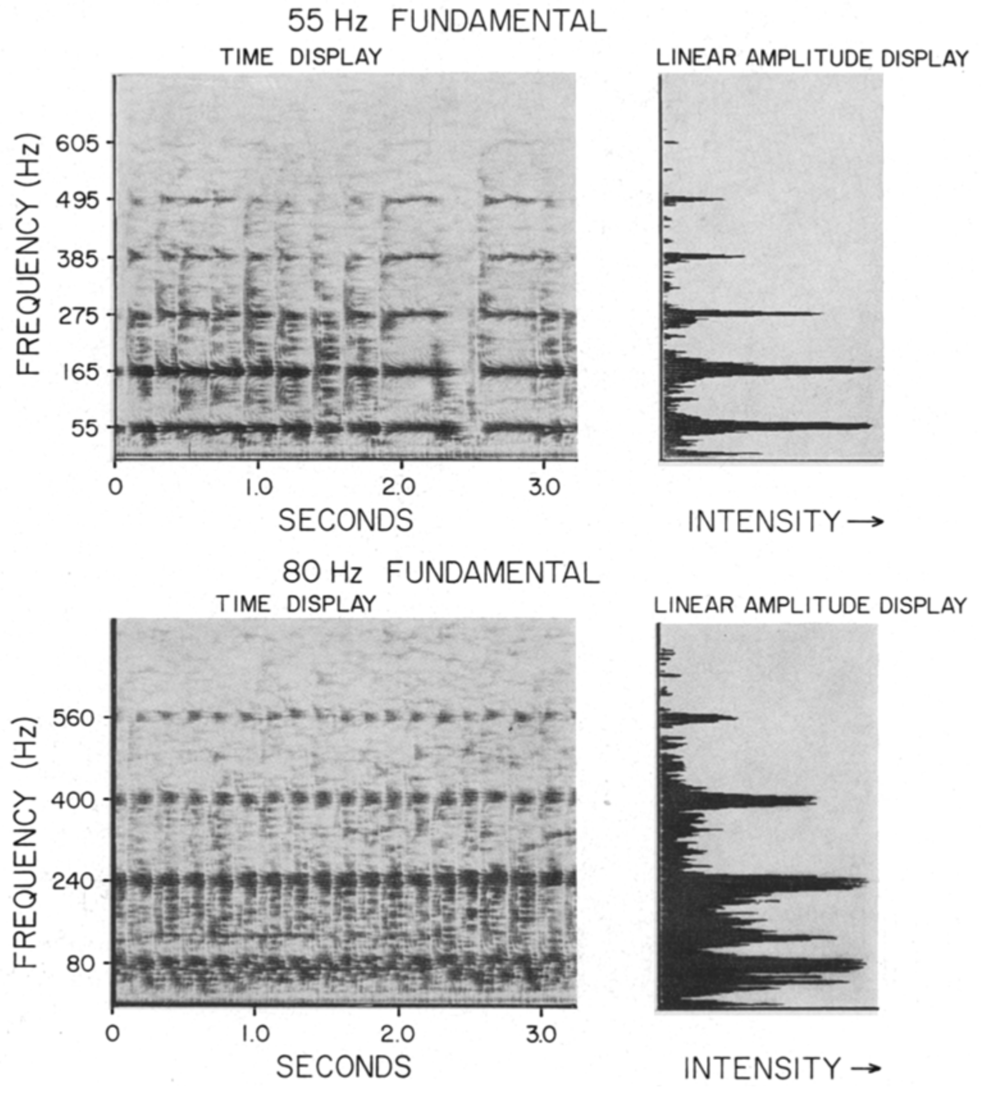

Fig. 4. Frequency and linear amplitude display of 2, pulsed, "overdriven" sine wave signals that were used in tests

The initial segment of the investigation, 18 through 20 March, 1967, dealt with attracting sharks by irregularly pulsed sine waves, both pure and "overdriven". This was followed by a 3 day period during which no sounds were transmitted. Testing then recommenced for 4 additional days.

A test period consisted of playing a given signal for 3 min. Silent (control) periods of equal duration bracketed each test period. A 1 min rest period, separating each test and control period, was instigated immediately after testing began, since sharks left the area of surveillance within 40 secs after transmission ceased. This rest period, therefore, allowed the control

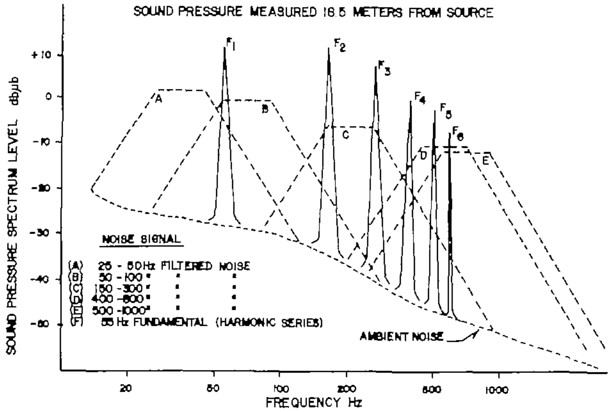

Fig. 5. Frequency displays of the filtered, broad-band signals (A to E) that were used in tests. The sound pressure of each display is shown relative to spectrum level noise, measured at the time of testing. The pressure level, relative to SPL noise, is also shown for the various harmonics of the overdriven sine wave that had as its fundamental, 55 Hz (F_1)

periods to reflect more accurately the differences in the presence of sharks between times when signals were transmitted and times when they were not.

Besides recording general observations, three measures of shark activity were quantified. First, the duration between the onset of a given period and the arrival of the first shark was recorded in seconds. Rapid panning of the camera (a single 360° sweep took about 7 sec) provided a reasonable estimate of this time. After the first arrival, a slower, but consistent, rate of panning (360° sweep — 20 sec) was maintained for the remainder of the period. This last procedure, sustained during the first segment of the study, was altered in the second segment by setting the camera at a fixed reference point after the first arrival of a shark.

As a reasonable measure of the motor activity of sharks around the UTV, the total sightings for a given period were determined by the number of times that individuals passed through the field of view. Restrictions to this count were imposed only when the camera was moving. In that case, a sighting was recorded only when a shark entered the field of view from the direction to which the camera was being panned at the moment.

Finally, the maximum number of sharks seen at a single time on the monitor screen was also recorded for each period. This was termed the maximum simultaneous sightings for a given period.

Shark identifications, and later verification of all counts, were made from videotape records of the entire study.

Acoustic attraction of sharks: effectiveness of various signals

The first few experimental series showed conclusively that sharks were attracted to acoustic signals having characteristics of irregularly pulsed, "overdriven" sine waves (Fig. 6). Each series, covering a different time — morning, noon, and late afternoon, also demonstrated that sharks can be attracted to a sound source at any time of the day. Additionally, trends in the data indicated decreasing numbers of sharks at the site during successive test periods. Habituation of the approach response after repeated presentation of an acoustic stimulus without positive reinforcement, would certainly influence any conclusions derived from this study, and experimental designs for future testing. We, therefore, checked on this possibility 1 h after Series 2 had been completed by transmitting irregularly pulsed, "overdriven" sine waves with 80 Hz fundamental (resulting signal from the hydrophone is illustrated in Fig. 4). Sound levels were held constant throughout the series. Fig. 7 illustrates clear habituation throughout the series, when viewed either as to the total shark sightings or as to the maximum simultaneous sightings per given period. Minimum time required to regain a prehabituation level of sightings was not investigated, but such a level was recorded during the following series (Series 3, Fig. 6) held about 1 h later.

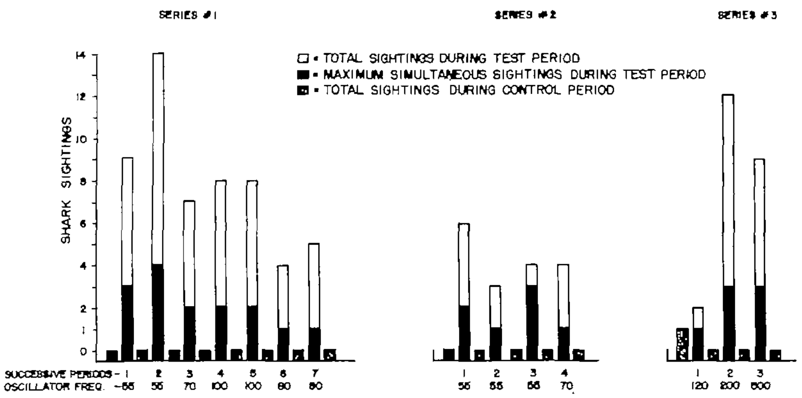

Fig. 6. Attraction of sharks by acoustic signals. Signals consisted of irregularly pulsed, overdriven sine waves (biphasic, symmetrical and distorted square waves). Peak sound pressure level at 18.5 m from sound source was approximately 20 dB above broad-band ambient noise. Each test and control period — 3 min. Start of Series 1 — 1650 h, Series 2 — 0920 h, Series 3 — 1300 h

After ceasing transmission for a few hours we examined, next, the possibility that pulsed signals of moderate frequencies could attract sharks. Tests included frequencies that NELSON and GRUBER (1963) had reported as being ineffective. Signals were again "overdriven" sine waves (oscillator frequencies given in Fig. 8). Testing began at the highest oscillator frequency, 1500 Hz, with subsequent lowering of frequency after each second test. Fig. 8 shows that sharks did not appear at the surveillance site, either during control periods or during periods when the acoustic signals had oscillator frequencies set above 800 Hz. The first shark (*Rhizoprionodon* sp., sharpnose) appeared during the first test, using 800 Hz as the fundamental. This individual arrived late in the test (141 sec after onset of transmission) and its behavior varied considerably from that normally shown by sharks arriving at the site (p. 273). It moved slowly and close to the bottom, the anterior portion of the body swaying slightly to each side as it moved through the area. It passed close by the sound projector and then swam off the site, not to return during the remainder of the test period. No sharks appeared during the second test, using this particular frequency. When the oscillator frequency was reduced, however, to 500 Hz, numerous sharks appeared rapidly. Attraction was observed during subsequent tests of the series, although habituation to the transmitted signals was again apparent.

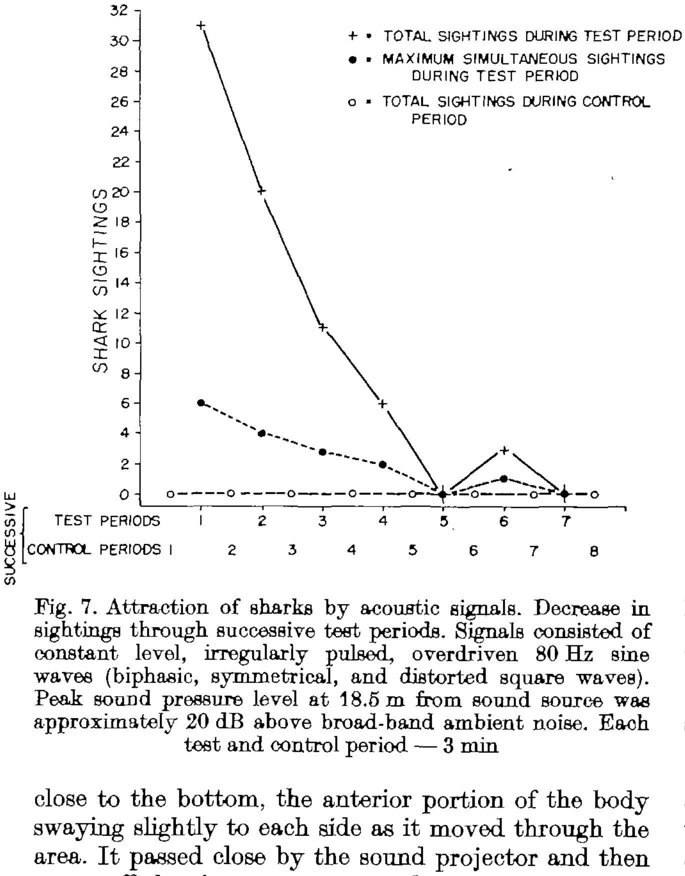

Fig. 7. Attraction of sharks by acoustic signals. Decrease in sightings through successive test periods. Signals consisted of constant level, irregularly pulsed, overdriven 80 Hz sine waves (biphasic, symmetrical, and distorted square waves). Peak sound pressure level at 18.5 m from sound source was approximately 20 dB above broad-band ambient noise. Each test and control period — 3 min

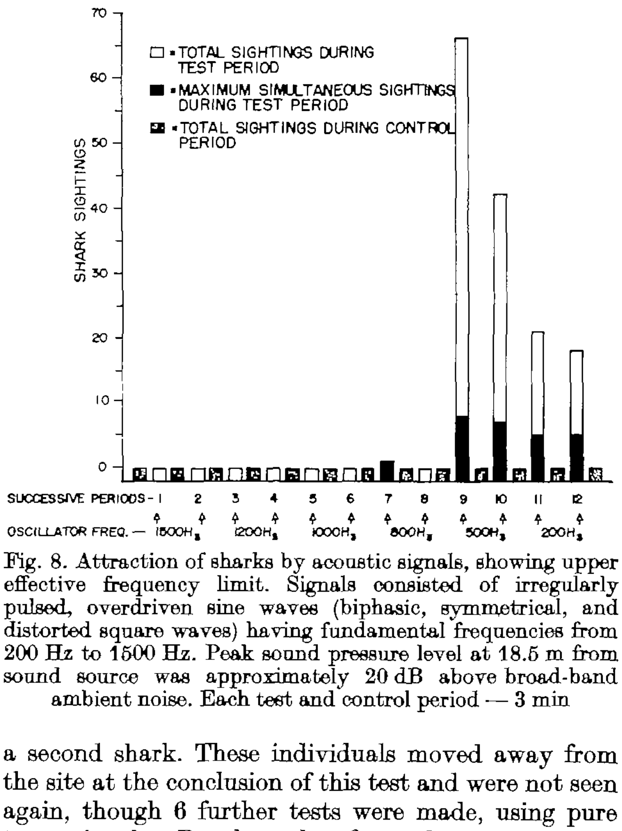

Fig. 8. Attraction of sharks by acoustic signals, showing upper effective frequency limit. Signals consisted of irregularly pulsed, overdriven sine waves (biphasic, symmetrical, and distorted square waves) having fundamental frequencies from 200 Hz to 1500 Hz. Peak sound pressure level at 18.5 m from sound source was approximately 20 dB above broad-band ambient noise. Each test and control period — 3 min

Tests were not designed to investigate the low frequency limit for attraction, since the lowest frequency obtainable with the equipment during the first segment of the study was 55 Hz. This signal had already attracted a good number of sharks (Fig. 6).

The final series of the first segment of the study tested possible attraction of sharks by irregularly pulsed, pure sine waves (i.e., pure tones). This series was run on the day following the preceding series, so as to lessen any possible effects of prior habituation to non-reinforced acoustic signals. Results of these tests, covering frequencies between 55 Hz and 1500 Hz, were negative (Table 1). To verify that sharks were in the area, one test period, using an "overdriven" signal, was interposed midway through the series. This signal had an oscillator frequency of 80 Hz and an amplitude approximately that of the pure tone signals. As before, this "overdriven" signal was effective in attracting sharks. The first shark arrived at the site 41 sec after the onset of the period, followed shortly thereafter by a second shark. These individuals moved away from the site at the conclusion of this test and were not seen again, though 6 further tests were made, using pure tone signals. Results, therefore, demonstrate the ineffective use of the latter signals for purposes of attraction in the absence of apparent reinforcement.

Following a 3 day break in testing, the second segment of the study investigated far-field hearing and orientation, as well as the effectiveness of pulsed, broad-band signals in attracting sharks. The latter series, though run last, will be treated first, since its results are comparable to those of the previous testing.

Five bands (Fig. 5) were transmitted in the following succession, each comprising a separate test period; 25 to 50, 500 to 1000, 50 to 100, 400 to 800, and 150 to 300 Hz. This succession was played through twice, followed by additional tests at the highest frequency noise band. Control periods again bracketed each test. Results are given in Table 1. The filtered, broad-band signals were obviously more attractive than pure tones, but apparently less so than the "overdriven" sine waves. The number of sharks present in the area may have changed, however, during the intervening 3 days between segments of the study.

(C) One individual, identified as either the silky shark *C. falciformis* (MÜLLER and HENLE) or the dusky shark *C. obscurus* (LE SUEUR), during 2 periods.

(D) One nurse shark, *Ginglymostoma cirratum* (BONNATERRE), during 1 period.

Controls One nurse shark during 1 period.

Table 1. *Acoustic attraction of sharks: summary of experimental series*

	Total number	Total shark sightings
Control period	87	6
Test period	74	375

Breakdown of test periods

Acoustic signal (irregularly pulsed)	Number of periods	Total shark sightings	Maximum simultaneous shark sightings per period	Time between onset of signal and first shark sighting (sec)
Overdriven sine waves[a]				
55	5	37	4	28—46
70	2	12	2	30—51
80	9	83	6	23—76
100	2	16	2	22—31
120	1	2	1	125
200	3	51	5	27—31
500	3	117	8	11—54
800	2	1	1	141
1000	2	0	0	—
1200	2	0	0	—
1500	2	0	0	—
	Total 33	319		
Broad-band filtered				
25—50	2	2	1	110
50—100	2	5	2	45
150—300	2	2	1	122
400—800	2	3	1	21
500—1000	9	44	5	14—32
	Total 17	56		
Pure sine waves				
55	1	0	0	—
80	4	0	0	—
120	1	0	0	—
200	2	0	0	—
400	2	0	0	—
500	5	0	0	—
600	2	0	0	—
700	2	0	0	—
800	2	0	0	—
1000	1	0	0	—
1200	1	0	0	—
1500	1	0	0	—
	Total 24	0		

[a] Alternating, symmetrical and distorted square waves including harmonics.

The following is a summary of those species of sharks observed during all previous testing:

"Overdriven" sine waves:

Tests (A) Almost all were sharpnose sharks, *Rhizoprionodon* sp., probably *R. porosus* (POEY), during all periods.

(B) One or two reef sharks, *Carcharhinus springeri* BIGELOW and SCHROEDER, during 3 periods.

Broad-band signals:

Tests (A) Almost all were sharpnose sharks during all periods.

(B) Two reef sharks during 2 periods.

(C) One nurse shark during 1 period.

(D) One very heavy-bellied, large shark passed rapidly above the UTV housing during 1 period. Only the lower portion of the body was seen on the monitor;

Table 2. *Species of free-ranging sharks that have been attracted to a sound source immediately following the generation of an acoustic signal*

Species	Common name	Acoustic signal	Author
Carcharhinus springeri	Reef	Instrumental, pulsed	This text
C. leucas	Bull	Instrumental, pulsed	NELSON and GRUBER (1963)
C. menisorrah	Grey	"...speared fish..."	HOBSON (1963) EIBL-EIBESFELDT and HAAS (1959)
C. lamiella	Bay	"...splashing..."	LIMBAUGH (1963)
C. galapagensis	Galapagos	"...speared fish..."	LIMBAUGH (1963)
C. platyrhynchus (= *C. albimarginatus*)	Silvertip	"...commotions..."	LIMBAUGH (1963)
C. falciformis or *C. obscurus*	Silky or Dusky	Instrumental, pulsed	This text
Rhizoprionodon sp. (probably *R. porosus*)	Sharpnose	Instrumental, pulsed	This text
Sphyrna sp.	Hammerhead	Instrumental, pulsed	NELSON and GRUBER (1963)
Galeocerdo cuvieri	Tiger	Instrumental, pulsed	NELSON and GRUBER (1963)
Negaprion brevirostris	Lemon	Instrumental, pulsed	NELSON and GRUBER (1963) BANNER (1968)
Ginglymostoma cirratum	Nurse	Instrumental, pulsed	This text

it did not appear to be one of the above mentioned species.

Controls Five sharpnose sharks during 1 period; three swam by, near the limit of visibility, as a powerboat was passing overhead, two more individuals followed 5 sec later.

Although our tests involved only a few species of sharks in one location, the results strongly suggest that substantial bandwidth and pulse modulation are 2 essential characteristics of an attractive acoustic signal. Information on the relative effectiveness of different frequency bands was obscured by the rapid habituation to acoustic signals during any given test series. Also, comparison between tests separated by a substantial time interval was difficult to make because of probable diurnal variations in populations and behavior.

Unfortunately, only a few audiograms have been obtained for sharks, and none for the species encountered here. Evidence to date indicates that the shape of the audiogram varies considerably among shark species, depending perhaps on their feeding habits. For example, surface feeding sharks may be more sensitive to relatively higher frequency, splashing sounds, than bottom feeding sharks, which in turn, may be more sensitive to relatively lower frequency, hydrodynamic sounds. In any event, the audiogram shape and ambient noise spectra are 2 factors which must be considered when comparing the effectiveness of different frequencies, as they both determine the subjective loudness of a given test signal.

Although conclusions cannot be drawn at this time regarding the relative effectiveness of different frequencies, bandwidths, and pulse repetition rates, our results and those of earlier tests suggest that the modulation characteristics of an acoustic signal represent a primary attracting component. Presumably, these pulse modulated sounds simulate the noise bursts generated either by physical movements of prey (BANNER, 1968) or by predators actively feeding.

Since there are many possible combinations of the variables mentioned above, a large number of tests will have to be made to resolve the question of optimal signal characteristics and possible variations in species preference. Table 2 lists those species of free-ranging sharks that have, as yet, been identified, after rapid arrival at a given sound source. This list will surely grow as more published information becomes available.

Acoustic attraction of sharks: low level signals

The utility of a sensory receptor system is determined, to a large extent, by the distance over which it operates. This is particularly important for predators in regard to the means by which they detect prey. The ability to detect and to localize sounds will be most useful to sharks if it extends beyond the effective ranges of ~~vision~~ and olfaction, or in other words, beyond the limits of the acoustic near-field. The near-field is typically defined as the region within a distance of about one wave length from a sound source (HARRIS and VAN BERGEIJK, 1962). Relatively large displace-

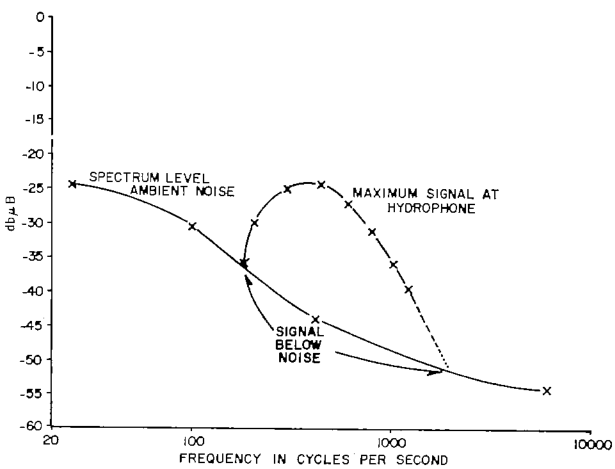

Fig. 9. Pressure levels of the minimum amplitude signal (relative to spectrum level ambient noise) effective in attracting sharks during the far-field tests

ments of the medium predominate in the near-field. In contrast, a far-field signal is characterized by relatively minute displacements associated with the propagated compressional wave. Although it is generally conceded that sharks may hear sounds from considerable distances, it is still widely believed that they are not able to orient to a sound source when in the far-field, despite evidence to the contrary (KRITZLER and WOOD, 1961; NELSON, 1967b). A test series was therefore designed to supply still further information regarding this problem.

This particular series followed, immediately, the 3 day rest period between segments of the investigation. This reduced the probability that sharks "called-in" during previous testing would still be in the immediate area of the UTV site. Divers also scouted the site immediately prior to testing and reported that no sharks were evident within a 50 m radius of the UTV.

Table 3. *Far-field attraction of sharks. Signal: irregularly pulsed noise; components above spectrum level ambient noise — between approximately 190 Hz and 3000 Hz; Minimum distance of attraction: beyond position of hydrophone (18.5 m from sound projector); Limit of near-field—10 m. No sharks sighted during control periods which bracketed each test*

Test No.	Signal amplitude (400 Hz) at hydrophone dB µB	Å	Total shark sightings	Maximum simultaneous shark sightings during period
1	—14	.06	16	4
2	—24	.02	6	2
3	—33	.01	0	0

Further testing prohibited because of decreasing light

Signals having relatively short wavelengths were used, so that the entire near-field lay well within the range of visibility (20 to 25 m). A broad-band signal was chosen with frequency cut-off at 500 and 1000 Hz. The filter provided a 50 dB attenuation of the signal at 100 Hz, so it, as well as all lower frequencies, was substantially below spectrum level ambient noise, as shown in Fig. 9.

Table 3 summarizes the effectiveness of these irregularly pulsed signals in attracting sharks, as well as the signal amplitudes used in testing, expressed in pressure and displacement values at the hydrophone. Displacement was calculated from the equation: $d = \frac{p}{\omega \varrho c}$ (HARRIS and VAN BERGEIJK, 1962; HARRIS, 1964). Fig. 10 shows characteristics of the lowest amplitude signal found to be effective for attracting sharks to the UTV site. It should be emphasized that all sharks arrived from distances at least 5 m beyond

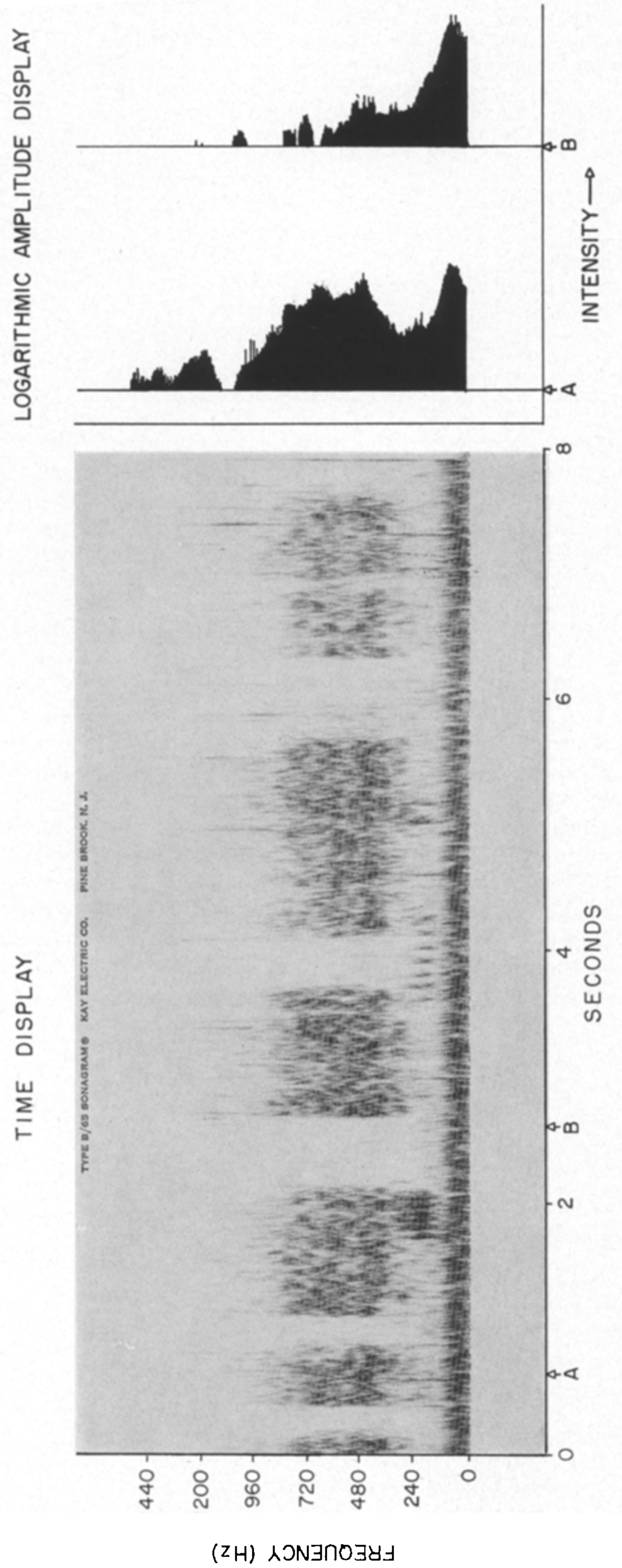

Fig. 10. Frequency and logarithmic amplitude displays of the minimum amplitude signal effective in attracting sharks during the far-field tests. Point A: signal and ambient noise; Point B: ambient noise alone. The signal consisted of a noise band having components above spectrum level noise between approximately 200 Hz and 3000 Hz. Peak signal was about 400 Hz

the hydrophone, many passing almost directly above it, as they moved onto the site. Their rapid swimming speed, the time of first arrival (32 sec), and the direct approach, impressed the observers with the sharks' apparent "homing" abilities. Control periods, bracketing all tests, recorded not one shark sighting. Decreasing light precluded further testing after 6 test and control periods.

Since perception of acoustic stimuli by sharks is not limited to the near-field, their hearing range must be determined by the level of the signal in relation to background noise. The minimum effective signal, as seen in Fig. 10, was less than 20 dB above spectrum level ambient noise at 400 Hz, when measured as pressure. Thresholds of young lemon sharks, tested in the laboratory, were also about 20 dB above spectrum level noise at 320 Hz, when measured as displacement (BANNER, 1967). Unfortunately, signal to noise ratios from field and laboratory experiments are not directly comparable. Threshold values that have been obtained for the bull shark at 400 Hz, while being tested in a large enclosure, were below filtered noise (KRITZLER and WOOD, 1961). These values, however, would most probably have been above the spectrum level of that noise. Also, as in our study, signal and noise were measured as pressures, and so their ratio may not be equal to that received by displacement receptors of the test subject. In any event, pressure and displacement levels of the lowest effective signal (Table 3) are remarkably low. Attraction by such weak signals indicates the importance of acoustic stimuli to these animals.

Behavior of sharks at the UTV site

During the investigation, note was taken of the behavior of those sharks under surveillance. Most observations involved the sharpnose shark (*Rhizoprionodon*) as it was the most abundant species around the UTV site. The behavior of other species was of special interest for purposes of comparison. Sharks arrived rapidly on the scene (sharpnose always first), usually 20 to 40 sec after the onset of the acoustic signal, with an apparent straight-line approach into the region of the sound source. Sharpnose sharks moved onto the site at heights of about 2 to 3 m above the bottom; the larger requiem sharks (*Carcharhinus*) were first spotted slightly higher in the water column (4 to 5 m), while nurse sharks (*Ginglymostoma*) moved onto the site just off the bottom. In 2 cases, individuals rapidly approached the sound projector (one sharpnose and one nurse) and either rammed it or bit it. Similar "attack" behavior on a sound projector has also been observed in immature lemon sharks in Biscayne Bay, Florida (BANNER, 1968).

Nurse sharks arrived on the site singly during 3 periods, and each moved off within a minute or two. Requiem sharks often arrived within seconds of one another and, with but a few exceptions, began circling just within visible range. Since the UTV and the sound projector were relatively near one another, we couldn't determine which instrument, or if both, were actually being circled. This peculiar circling behavior is probably the most consistently mentioned activity of sharks in the vicinity of a stimulus object (EIBL-EIBESFELDT and HAAS, 1959; HOBSON et al., 1961), and is probably the result of the inability of sharks to maintain position in the water column without moving.

As sharks increased in number during a given test, locomotory activity also appeared to increase. This, in turn, was often associated with tighter circling and criss-crossing of the site. These activities were augmented when turbidity increased or ambient light level decreased.

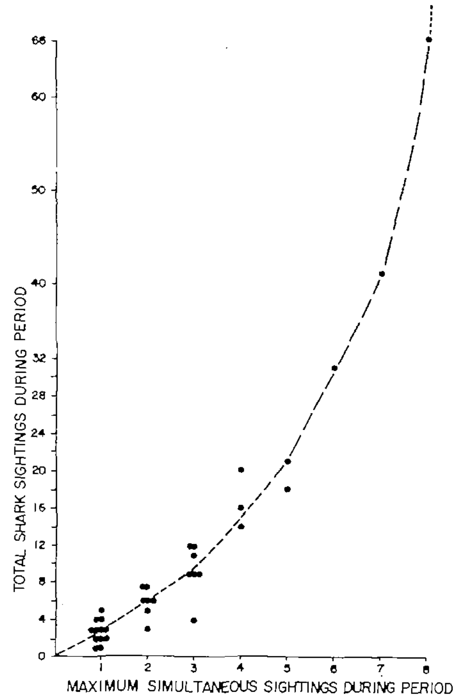

Fig. 11. Correlation between total shark sightings per period (measure of activity) and the maximum simultaneous sightings during the same period (measure of numbers). Dotted line determined by eye

After all testing was completed, a clear relationship was found to exist between the maximum simultaneous sightings per period and total shark sightings for the same period (Fig. 11). Although based on limited data, the increasing steepness of the curve describing the relationship of these 2 factors strongly suggests that, as the number of sharks increased in the area, motor activity of each shark also increased. This rapid increase in activity, probably brought about by some type of social facilitation, is consistent with general observations by others (ESSAPIAN, 1962; SPRINGER, 1967) and it provides insight into the possible causes and maintenance of "frenzies" in free-ranging sharks, either in the presence, or absence, of food. Although sharks were not seen to collide or bite one another, as has been seen by others during "feeding frenzies", individuals occasionally made rapid and direct passes at small, low profile, rocky outcrops, as well as occasionally shaking their heads slightly from side to side, prior to rapid acceleration. Rapid jaw-spreading, as in a yawn, was also seen occasionally in sharks that were moving in tight circles. Such activities have been observed in other sharks during feeding periods (Eibl-Eibesfeldt and Haas, 1959). When circling became tighter (e.g., 10 m dia.), and criss-crossing of the site began, 2 or 3 sharpnose sharks often swam parallel for distances exceeding 15 m and their individual spacing was judged to be somewhat less than 1 m. Based upon their ability to maintain close spacing during occasional rapid maneuvering, the species appeared fully capable of schooling in the restricted sense of the term, for at least short distances. Such coordinated swimming, though not seen in the larger requiem sharks, has also been observed in young lemon sharks (personal observation).

After signal transmission ceased, circling spread out and, shortly thereafter (20 to 40 sec), individuals moved off the site, singly or in small groups. Although the sharpnose sharks often moved within a meter or two of the bottom when at the site, their exit was about the same depth as their arrival. No interspecific interaction between sharks was seen during the investigation.

The constant activity of sharks during testing prevented exact records being kept on the bony fishes that also had been attracted. Those identified from the video recording included groupers (Nassau *Epinephelus striatus*; yellow-fin *Mycteroperca venenosa*; black *M. bonaci*) and snappers (gray *Lutjanus griseus*; mutton *L. analis*; yellowtail *Ocyurus chrysurus*). Groupers arrived singly or, at most, in twos, while snappers came in small groups. Bony fishes generally arrived only after several minutes of transmission, reaching the site long after sharks had arrived. Groupers often approached slowly, came to rest in front of the sound projector, and slowly drifted off the site after 10 to 30 sec of transmission. Although large groupers and snappers did arrive at the site when sharks were present, their numbers appeared to be inversely related to the number of sharks present. The sounds transmitted must certainly possess common elements attractive to all these predators. These observations on attraction of teleosts agree well with those of Richard (1968).

General conclusions

The actions of sharks have often been described as unpredictable. This conclusion may reflect, at least to some extent, the inadequacy of our knowledge concerning relationships between various environmental factors and specific motor activities of sharks. As our knowledge of these relationships increases, so will our ability to predict and even control, in some cases, the behavior of these animals. Technical systems, such as the Bimini Video-Acoustic Installation, when properly conceived and used, will aid this effort immeasurably. The advantages of such a system for purposes of field observation and experimentation have provided a clear idea of the important role that the sonic environment has in directing at least some activities of sharks.

Combining our results with those of previous reports, there can be little doubt that, if sharks are within audible range, these animals can be rapidly attracted to the region of a sound source that is transmitting irregularly pulsed signals, having components below 800 Hz (how near they will approach the source will probably depend on other stimulus qualities of the source, e.g., its size). Signals, having audible components only above 1000 Hz or in the form of pure sine waves, will probably not be attractive in the absence of some type of positive reinforcement. It also appears that sharks learn rather rapidly to ignore an acoustic signal that does not have some element of reward. Evidence has been presented for attraction from distances beyond the acoustic near-field, and strongly suggests acoustic orientation from considerable distances. The effective signal levels for purposes of such attraction can be remarkably low. Individual motor activity of sharks in the region of a stimulus source is augmented as the population density increases. The distance at which sharks circle the source is also related to numbers present and to conditions of visibility.

Summary

1. The present study demonstrates the usefulness of underwater television, when coupled with appropriate acoustic equipment, for performing detailed field experiments on free-ranging sharks, and points to the increasing use of this tool in future research on marine biological phenomena.

2. Acoustic signals, represented by overdriven sine waves and filtered, broad-band noise, attracted sharks of the following species: sharpnose shark *Rhizoprionodon* sp. (probably *R. porosus*); reef shark *Carcharhinus springeri*; nurse shark *Ginglymostoma cirratum* and either the silky shark *C. falciformis*, or the dusky shark *C. obscurus*. Groupers and snappers were also attracted to the above sounds, but shark activity precluded recording specifics about the attraction of bony fishes.

3. Frequencies attractive to sharks ranged from at least 55 Hz to between 500 and 1000 Hz. This extended the upper frequency limit of attractive signals from that determined by Nelson and Gruber (1963) and Nelson (1967 b).

4. The upper frequency limit for purposes of attraction appeared to be around 800 Hz. This agreed closely with the upper frequency limit of sound perception, as demonstrated by laboratory experiments on the lemon shark *Negaprion brevirostris*. This means that moderate frequencies, as well as low frequencies (20 to 100 Hz), are important attractants to sharks of various species.

5. Signals produced by overdriving sine waves appeared more attractive to sharks than filtered, broad-band signals, but further observations must be made to establish this beyond any doubt.

6. Pure tone signals and harmonic series sounds, having frequencies only above 1000 Hz, appear to be unattractive to sharks frequenting the Bimini site.

7. Sharks habituated rapidly to unreinforced acoustic signals, but regained pre-habituation levels of response within 1 h.

8. Sharks appeared fully capable of not only perceiving an acoustic signal within the far-field, but of orientating directionally to a given sound source from this same area.

9. Swimming activity of sharks increased rapidly within a given area as their number increased. This was especially so when sharks exceeded 3 in number. This relationship gives added insight into the problem of the so called, "shark frenzy". Tighter circling and criss-crossing of the surveillance site also increased when turbidity increased or ambient light level decreased.

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