

Measurements of the low frequency components of active and passive sounds produced by dolphins

Paul E. Nachtigall¹, Whitlow W. L. Au¹, Jeffrey L. Pawloski¹, Kimberly Andrews¹
and Charles W. Oliver²

¹Hawaii Institute of Marine Biology, University of Hawaii, P.O. Box 1106, Kailua, Hawaii 96734, USA

²NOAA, National Marine Fisheries Service Science Center, La Jolla, CA, USA

Abstract

Low frequency components of whistles, tailslaps, breaches, and jaw claps were recorded from a trained Pacific bottlenose dolphin *Tursiops truncatus* located in open bay pens at the Hawaii Institute of Marine Biology in Kaneohe Bay, Hawaii. Peak to peak pressure levels for breaches ranged between 168 to 181 dB re 1 μ Pa, and fluke produced tail slaps ranged between 166–175 dB re 1 μ Pa. RMS measurements of whistles ranged between 143 and 153 dB re 1 μ Pa, while peak to peak jaw clap sounds were at least 172 dB re 1 μ Pa. Most of the energy occurred below 2 kHz. These measured levels are louder than have typically been reported and the results are discussed in terms of potential dolphin-tuna associations.

Key words: dolphins, acoustics, sound amplitudes.

Introduction

In the eastern tropical Pacific Ocean, yellowfin Tuna, *Thunnus albacares*, commonly associate with a variety of odontocete cetaceans including the spinner dolphin, *Stenella longirostris*, and the pan-tropical spotted dolphin, *Stenella attenuata* (Perrin, 1969). Tuna fishermen frequently exploit this association by visually detecting the dolphins and setting nets around them. The air-breathing dolphins remain closer to the surface and can be seen from a greater distance than the tuna (National Research Council, 1992). The association between tuna and dolphins could be related to a common food source (Perrin *et al.*, 1973; Scott & Cattanach, 1998), but the relative acuity of tuna sensory abilities, which may facilitate the tuna-dolphin association, has not been critically examined.

Because there is a strong tuna-dolphin association, Schaefer & Oliver (2000) suggested there

must be some dominant sensory cue that allows the tuna and dolphins to maintain the contact. Given that it is likely that much of the prey capture by the spinner dolphins occurs at night, and at considerable depth, it seems reasonable that the tuna sense the presence of the dolphins acoustically rather than visually.

In a classic experiment, Iverson (1967) trained two captive yellowfin tuna to swim between two nets if a sound was presented and to swim straight if no sound was presented. Data from this behavioral audiogram experiment demonstrated that tuna heard best (e.g., most sensitive) between 200 and 800 Hz, and rapidly degraded above 1000 Hz. No measures of hearing of tuna for sounds above 2000 Hz were reported. Because most sounds produced by dolphin whistles and clicks are generally higher than 2000 Hz (Wartzok & Ketten, 1999), we examined sounds produced by dolphins that might be heard by tuna. While there are limited data available about tuna auditory capabilities and thresholds, it is likely tuna may be capable of hearing some portion of the sound produced as dolphin whistles, echolocation clicks, or tail and body slaps.

While tuna hearing has not been tested at frequencies above 2 kHz, and clupeids are evolutionarily distant from scombrids, Popper (1997) demonstrated that a clupeid prey, the American shad, *Alosa sapidissima*, of the bottlenose dolphin, *Tursiops truncatus*, can detect sounds up to 180 kHz with somewhat better detection in the areas of maximum frequency for echolocating dolphin clicks (Au, 1974, 1993). Popper speculated that the fishes' ability to detect these ultrasonic signals may be an example of convergent evolution in predator and prey, similar to that of moths and other insects that have evolved the ability to detect the echolocation calls of predatory bats. Astrup & Møhl (1993), using a classically conditioned heart rate response, earlier found that cod (*Gadus morhua*), more closely

Table 1. Sounds produced by dolphins (from Wartzok and Ketten, 1999).

Scientific name	Common name	Signal type	Frequency range (kHz)	Frequency near maximum energy (kHz)	Source level (dB re: 1 μ Pa)
<i>Stenella attenuata</i>	Spotted dolphin	Whistles	3–21	7–18	—
<i>Stenella clymene</i>	Clymene dolphin	Whistles	6–19	—	—
<i>Stenella coeruleoalba</i>	Spinner dolphin	Whistles			
		Pulse bursts	1–23	5–60	109–125
		Pulse	1–160		
<i>Stenella longirostris</i>	Long-snouted spinner dolphin	Whistle	1–20		
		Click	1–160	5–60	—
		Whistles	5–20		
<i>Stenella plagidon</i>	Spotted dolphin	Clicks	1–8		
		Clicks	7–18	—	
<i>Stenella styx</i>	Gray's porpoise	Whistles	6–24	8–13	—
		Whistles	4–7		
<i>Steno bredanensis</i>	Rough-toothed dolphin	Click	5–32	4–7	—
		Whistles	1–24	4–15	
<i>Tursiops truncatus</i>	Bottlenose dolphin	Clicks	10–160	110–130	218–228

related to tuna, had the ability to hear 38 kHz pulses at a threshold level of 194.4 dB. They indicated that while the thresholds for cod were too high for most sources of marine high frequency sound, they were low enough for the cod to detect echolocating odontocetes at a range of 10 to 30 m.

While large tuna are not prey of small dolphins, they are prey of larger echolocating predators (Brill *et al.*, 1992; Thomas *et al.*, 1988) including the false killer whale, *Pseudorca crassidens* (Seifert, 1999). Perhaps more importantly, tuna and dolphins share common small fish prey (Perrin *et al.*, 1973) suggesting that some mutual advantage may be present to cause the association between tuna and dolphins.

Sounds produced by wild spinner and spotted dolphins and closely related species are presented in Table 1. This summary, from a recent chapter by Wartzok & Ketten (1999), is primarily comprised of animal signals recorded in the field. There are a number of difficulties with data historically collected in the field, because both amplitude and frequency of acoustic signals are very difficult to measure accurately. First, there is a difficulty determining the actual source level (amplitude of the sound 1 m from its source) from the measured received level (level of the signal received at the hydrophone some unknown distance from the source). Many of the recordings were not calibrated for amplitude measurements. Since sounds, particularly at higher frequency, rapidly diminish in amplitude with distance, the actual intensity of the sound produced by the animal is difficult to precisely determine unless recorded directly in front of the animal's head at a known distance. Second, highly directional, high frequency signals produced

in dolphin echolocation beam patterns (Au, 1980), are difficult to precisely determine because the measured frequency of the click is very much dependent on where within the beam pattern the measurement is taken. Examples of these difficulties can be seen by examination of the data collected from wild bottlenose dolphins (Table 1). Only clicks collected by Au *et al.* (1974) and Au (1993) provide accurate amplitude and frequency data taken from a dolphin echolocating in its natural environment. The data reported by Dierks *et al.* (1971) and Evans (1973) were gathered properly, but both source level and frequencies are dramatically reduced, most likely due to the fact that they were gathered in tanks (Nachtigall *et al.*, 1994).

To ascertain precise acoustical data on the amplitude and frequency of sounds produced by spinner and spotted dolphins, one should capture the animals, maintain them in a natural seawater open environment, train them to complete echolocation tasks and to produce other natural sounds under stimulus control, and accurately place hydrophone receivers to record the signals. While there are no spinner or spotted dolphins in captivity available for acoustic research, there is a fine background of valid acoustic measures of the echolocation signals of the Atlantic bottlenose dolphin (Nachtigall & Moore, 1988; Au, 1993), and captive bottlenose dolphins are maintained in a natural environment at the Hawaii Institute of Marine Biology (HIMB), Coconut Island, Kaneohe Bay, Hawaii.

The purpose of this study was to obtain accurate acoustic measures of whistle, tail slap, and breaching sounds produced by bottlenose dolphins. We

speculated that these sounds are similar, in frequency and amplitude, to sounds produced by the spinner and spotted dolphins that associate with tuna in the eastern tropical Pacific Ocean.

Materials and Methods

The dolphins were housed at the Marine Mammal Research Program's floating pen facilities on the leeward side of Coconut Island in Kaneohe Bay, Hawaii. The pen complex measured 64×12.2 m and floated in waters about 12 m deep. The subject animal, a female adult Pacific bottlenose dolphin, *Tursiops truncatus*, named Kolohe weighed 178 Kg, measured 2.51 m in length, and was captured off the coast of Oahu Hawaii in 1987. Sounds produced as whistles, tail slaps, and breaches were recorded during sessions on either 22 April 1999 or 4 May 1999. Two spontaneously produced jaw claps, produced when Kolohe vigorously clapped her jaws together, were also serendipitously recorded.

The animal was trained, over a period of months, to produce a variety of sounds based on signals given by the trainer. Stimulus control was established for emitting whistles, slapping the flukes on top of the water, and jumping out of the water (breaching). The animal was trained to station at a position and maintain a consistent orientation to the hydrophone while recordings were obtained for tail slaps and whistles, thus assuring a known distance between source and receiver. All sound producing behaviors occur naturally, both in the wild and in captive situations. Breaching was deemed especially important given the similarity between this behavior and the active leaping and spinning exhibited by wild spinner dolphins.

All measurements were conducted with a specially constructed hydrophone having a spherical piezoelectric element that is flat to approximately 200 kHz. The hydrophone was connected to a variable gain filter and signals were recorded using a Sony DAT-8 recorder operating at a 48 kHz sample rate with a fixed gain at unity. Hydrophone depth was 1 m for all measurements. A 2 meter horizontal separation distance was maintained between the hydrophone and the dolphin's tail during tail-slap measurements, and between the hydrophone and the dolphin's head during measurements of jaw claps and whistles. Breaching sounds were measured with the hydrophone between 2.6 and 3.6 m from the point of impact assuring an accurate measure of the sound and the ample wetness of the person recording. Signals were clearly audible above the relatively low ambient noise produced by snapping shrimp (Au & Banks, 1998). The recorded data were digitized and subsequently analyzed with Cool-Edit software.

Results

Because the desired sound-producing behaviors are within the dolphin's natural behavioral repertoire, the animal was rapidly trained to whistle, tail slap and breach in response to simple visual signals. Sounds produced during breaches produced the highest amplitudes. Recorded peak-to-peak sound pressure levels for each of ten breaches are shown in Figure 1. The source level is the sound pressure level referenced to a distance of 1 m from the point of impact where the animal landed on the water after jumping into the air. The animal normally landed on its side after its snout touched a ball suspended approximately 3.5 m above the water. Sound pressure levels ranged between 168 and 181 dB re $1 \mu\text{Pa}$ with an average source level of 176 dB with a standard deviation of 4 dB. Recognizing that dB is a logarithmic scale and that there can not be a true standard deviation which would require a linear scale, the numbers provided are for general descriptive purposes of the variability and not for statistical precision.

An example of the time display from a breach sound and its corresponding spectrogram are shown in Figure 2. The first major excursion was probably due to the dolphin's body impacting the water's surface. The second major excursion was probably caused by an air mass forced under the water by the impact of the dolphin at the surface. Most of the energy produced by each breach was below 2 kHz, although some components extended as high as 14 kHz.

The dolphin slapping its flukes on the water surface produced the next highest intensity sound. The source levels for each of fifteen tail slaps are shown in Figure 3. The peak-to-peak source levels varied from 166 dB to 175 dB re $1 \mu\text{Pa}$. The average peak-to-peak source level from tail slaps was 173 dB with a standard deviation of 2 dB re $1 \mu\text{Pa}$. Nine of ten tail slaps produced source levels within a range of about 4 dB. An example of a sound produced by the dolphin slapping its flukes on the water surface and its corresponding spectrogram are shown in Figure 4. Spectrograms of slaps indicate that most of the acoustic energy was below 2 kHz.

The rms source levels for each of twenty-seven whistles are shown in Figure 5. These trained whistles did not show a great deal of variation in source level. Most whistles occurred within a range of 10 dB with a minimum of 143 dB and a maximum of 153 dB re $1 \mu\text{Pa}$. The average rms amplitude of the whistles was 149 dB with a standard deviation of 2.29 dB re $1 \mu\text{Pa}$.

The time domain envelope of two of the whistles and the corresponding spectrogram are shown in Figure 6. The envelope display shows the second

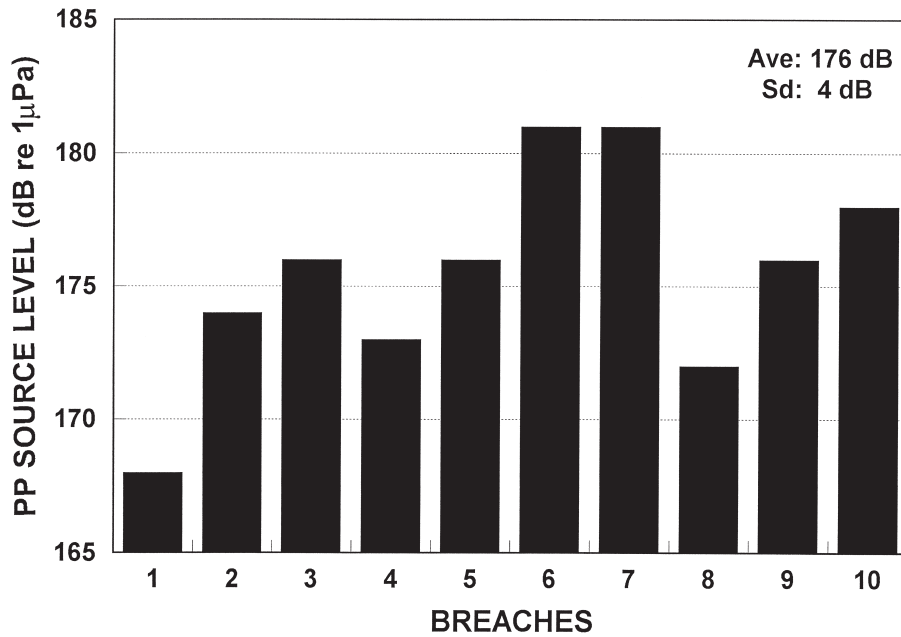


Figure 1. Peak source levels for ten bottlenose dolphin breaches.

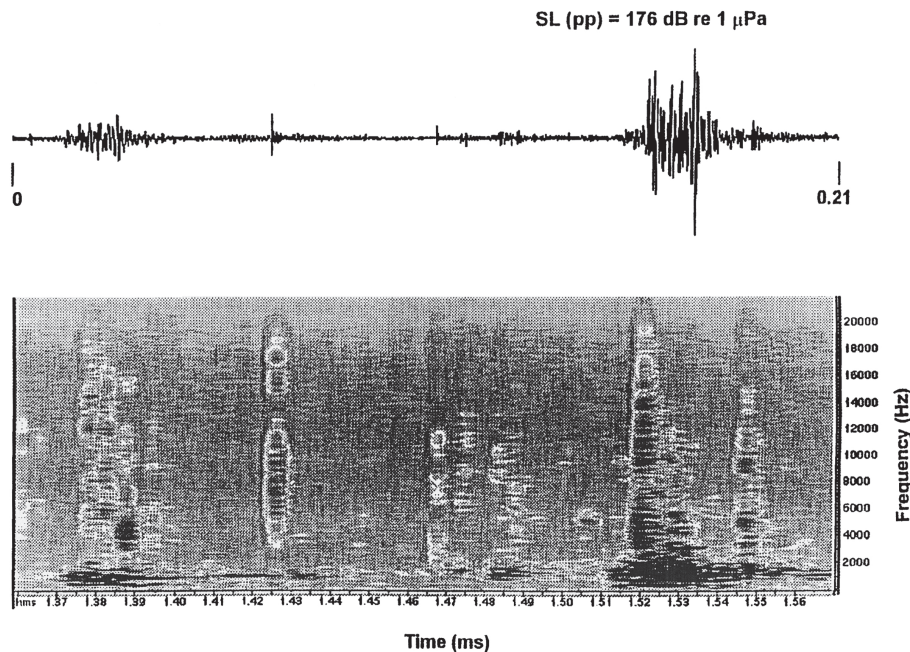


Figure 2. Oscillogram of a breach sound and the corresponding spectrogram.

whistle approximately 0.1 ms after the first whistle. Both whistles consisted of an upward sweeping, frequency-modulated signal increasing from 6 kHz to 20 kHz and then decreasing to about 6 kHz for the first whistle and 11 kHz for the second whistle.

Two jaw claps occurred and were serendipitously recorded when the dolphin approached the trainer. Unfortunately, both jaw claps caused the DAT recorder to saturate so we can only say that both jaw claps were at least 172 dB re 1 μPa.

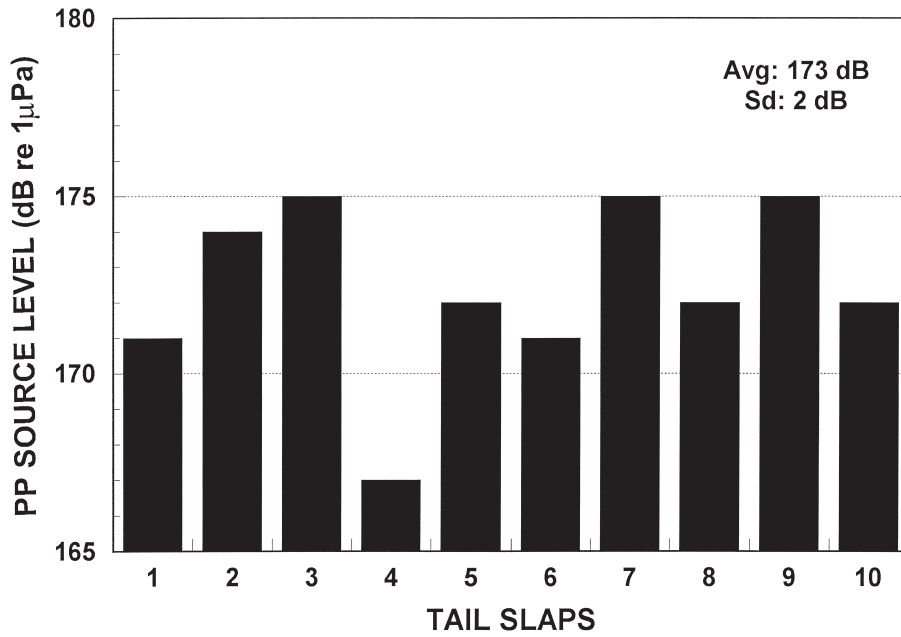


Figure 3. Peak to peak source levels from the sounds of 10 bottlenose dolphin tail slaps.

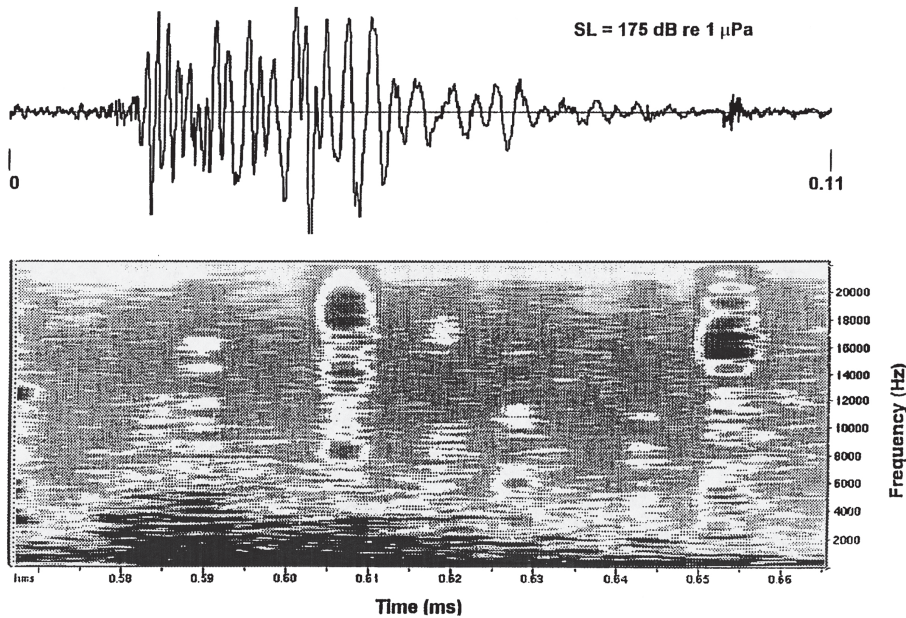


Figure 4. Oscillogram of a dolphin slapping its flukes and the corresponding spectrogram.

Discussion

Sound pressure levels measured from these four behaviors indicated that natural, low-frequency, sounds produced by dolphins are louder than

have typically been reported, but similar to those reported in a concurrently conducted study by Finneran *et al.* (2000). Most previous reports have not included measurements from the typical dolphin-produced sounds from breaching and tail

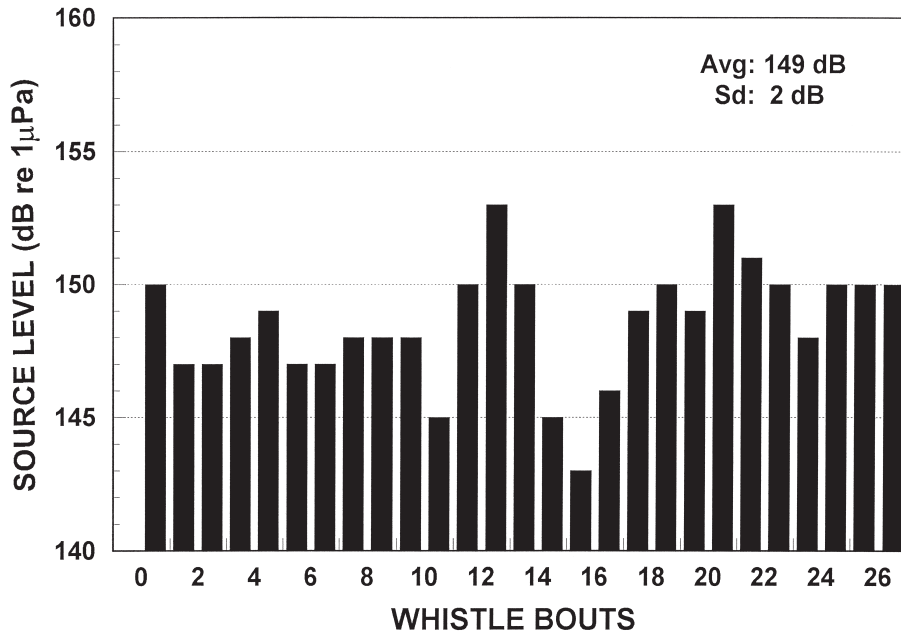


Figure 5. The source level of the recordings from 27 bottlenose dolphin whistles.

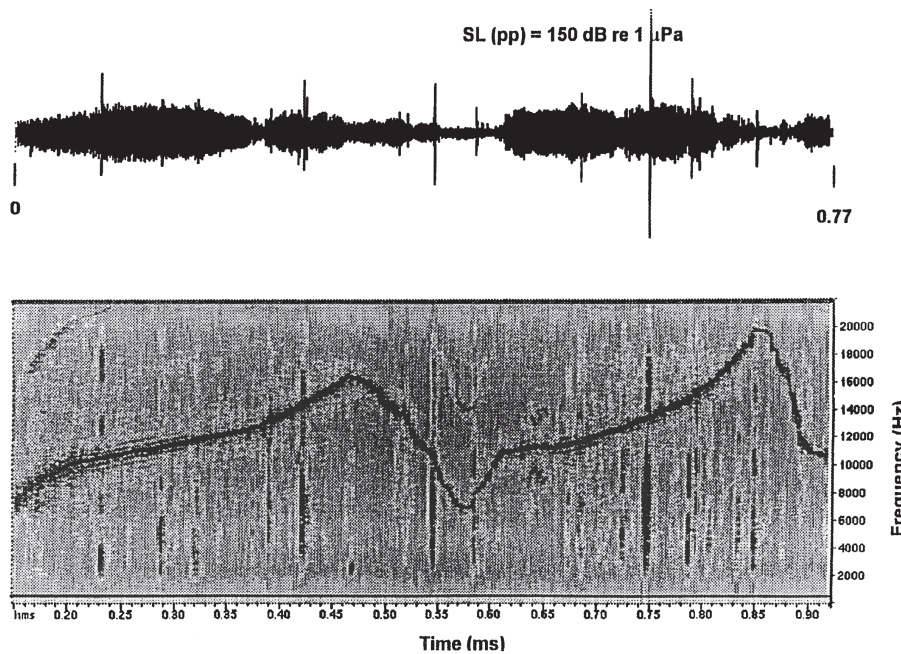


Figure 6. Oscillogram of the envelope and corresponding spectrogram of 2 dolphin whistles.

slap behaviors. All of the recorded source levels greatly exceed the hearing thresholds for the bottlenose dolphin (Johnson, 1996), at the appropriate frequencies and are therefore very likely heard by nearby dolphins. Also, all of the recorded sounds

contain ample amounts of the low frequency sounds that are heard by tuna.

Whistles have long been assumed to have a communicative function in odontocete cetaceans (Evans, 1967; Dreher & Evans, 1964; Lilly, 1962;

Sigurdson, 1993) and are frequently heard and recorded in the wild. Whistles could be especially important at night when feeding reportedly takes place with some species, particularly the spinner dolphin (Norris *et al.*, 1994). Although the animal in this study was trained to produce the whistles, our recorded source levels near 149 dB are within the range of those previously recorded for bottlenose dolphins in the wild, or opportunistically gathered in captivity (Wartzok & Ketten, 1999). The frequencies of our recorded whistles also fit well into the ranges previously recorded for bottlenose dolphins (e.g. McCowan *et al.*, 1998), with most of the energy found between 2 and 20 kHz. However, most of the energy in these whistles occurs above the apparent 1 kHz upper hearing threshold for yellowfin tuna, *Thunnus albacares* (Iverson, 1967). Popper's recent (1997) work on clupeid American shad hearing demonstrates that although these fish display a typical fish audiogram, with peak sensitivity below 1 kHz like the tuna, they also possess a second area of hearing sensitivity within the range of peak frequencies for odontocete echolocation clicks (25 and 130 kHz).

Yellowfin tuna associate with smaller echolocating odontocete cetaceans and are the prey of echolocating false killer whales (Seifert, 1999). If the clupeid American shad has developed a second area of hearing sensitivity in the ultrasonic range in response to predatory pressures of bottlenose dolphins, as suggested by Popper, we speculate that tuna may have also developed the ability to hear echolocation clicks between 25 and 130 kHz, in order to both localize symbiotic cetaceans and avoid predatory cetaceans as was demonstrated by Astrup and Møhl (1993) with the cod. It might be very interesting to reevaluate the hearing of yellowfin tuna, *Thunnus albacares*, in the frequency range of sounds produced by cetaceans while echolocating.

The sounds produced by breaches, tail slaps and jaw claps were relatively loud at 176, 173, and 172 dB re 1 μ Pa, respectively, and all displayed a preponderance of energy below 2 kHz. These signals contained acoustic energies most easily heard by yellowfin tuna, *Thunnus albacares*, as demonstrated in the only known tuna audiogram (Iverson, 1967). Certainly, the sounds produced by the acrobatic leaps of the spinner dolphin (Norris *et al.*, 1994) should equal the tail slaps and breaches of our bottlenosed dolphin and might be easily heard by the accompanying tuna.

Acknowledgments

This work was jointly supported by the Office of Naval Research Grant number N00014-98-1-0687 and National Marine Fisheries Service Grant

number 40JGNF800279. The authors appreciate the helpful reviews by Jakob Tougaard and an anonymous reviewer along with helpful comments from the Editor.

Literature Cited

- Astrup, J. & Møhl, B. (1993) Detection of intense ultrasound by the cod (*Gadus morhua*). *The Journal of Experimental Biology* **182**, 71–80.
- Au, W. W. L. (1980) Echolocation signals of the Atlantic bottlenose dolphin (*Tursiops truncatus*) in open waters. In: R. G. Busnel & J. F. Fish (eds) *Animal Sonar Systems*, Plenum Press, New York, pp. 251–282.
- Au, W. W. L. (1993) *The Sonar of Dolphins*. Springer-Verlag, New York, 277 pp.
- Au, W. W. L. & Banks, T. (1998) The acoustics of snapping shrimp, *Synalpheus parneomeris*, in Kaneohe Bay. *Journal of the Acoustical Society of America* **103**(1), 41–47.
- Au, W. W. L., Floyd, R. W., Penner, R. H. & Murchison, A. E. (1974) Measurement of echolocation signals of the Atlantic bottlenose dolphin *Tursiops truncatus* Montagu, in open waters. *Journal of the Acoustical Society of America* **56**, 1280–1290.
- Brill, R. L., Pawloski, J. L., Helweg, D. A., Au, W. W. L. & Moore, P. W. B. (1992) Target detection, shape discrimination, and signal characteristics of an echolocating false killer whale (*Pseudorca crassidens*). *Journal of the Acoustical Society of America* **92**, 1324–1330.
- Dierks, K. J., Trochta, R. T., Greenlaw, R. L. & Evans, W. E. (1971) Recording and analysis of echolocation signals. *Journal of the Acoustical Society of America* **49**, 1729–1732.
- Dreher, J. J. & Evans, W. E. (1967) Cetacean communication. In: W. N. Tavolga (ed.) *Marine Bioacoustics*, Volume 2, Pergamon, New York, pp 373–393.
- Evans, W. E. (1967) Vocalization among marine mammals. In: W. N. Tavolga (ed.), *Marine Bioacoustics*, Volume 2, Pergamon, New York, pp 159–186.
- Evans, W. E. (1973) Echolocation by marine delphinids and one species of fresh water dolphin. *Journal of the Acoustical Society of America* **54**, 191–199.
- Finneran, J. J., Oliver, C. W., Schaefer, K. M. & Ridgway, S. H. (2000) Source levels and estimated yellowfin tuna (*Thunnus albacares*) detection ranges for dolphin jaw pops, breaches, and tail slaps. *Journal of the Acoustical Society of America* **107**(1), 649–656.
- Iverson, R. T. B. (1967) Response of yellowfin tuna (*Thunnus albacares*) to underwater sound. In: W. N. Tavolga (ed.) *Marine Bioacoustics*, Volume 2, Pergamon Press, New York, pp 105–122.
- Johnson, C. S. (1966) Auditory Thresholds of the bottlenosed porpoise (*Tursiops truncatus*, Montague). U.S. Naval Ordnance Test Station Technical publication 4178, China Lake, California.
- Lilly, J. C. (1962) Vocal behavior of the bottlenose dolphin. *Proceedings of the American Philosophical Society* **106**, 520–529.
- Mann, D. A., Lu, Z. & Popper, A. N. (1997) A clupeid fish can detect ultrasound. *Nature* **389**, 341.
- McGowen, B., Reiss, D. & Gubbins, C. (1998) Social familiarity influences whistle acoustic structure in adult

- female bottlenose dolphins (*Tursiops truncatus*), *Aquatic Mammals* **24**(1), 27–40.
- Nachtigall, P. E. & Moore, P. W. B. (1988) *Animal Sonar: Processes and Performance*. Plenum Press, New York, 862 pp.
- Nachtigall, P. E., Au, W. W. L., Pawloski, J. L., & Roitblat, H. L. (1994) Animal echolocation and signal processing. *Oceans 94: Proceedings of the IEEE*, **1**, 259–263.
- National Research Council, Committee on Reducing Porpoise Mortality from Tuna Fishing (1992). *Dolphins and the Tuna Industry* (National Academy Press, Washington, DC).
- Norris, K. S., Würsig, B., Wells, R. & Würsig, M. (1994) *The Hawaiian Spinner Dolphin*. University of California Press, Berkeley.
- Perrin, W. F. (1969) The problem of porpoise mortality in the U.S. tropical tuna fishery. In: Thomas C. Poulter (ed.) *Proceedings of the Sixth Annual Conference on Biological Sonar and Diving Mammals*, Stanford Research Institute, Palo Alto CA.
- Perrin, W. F., Warner, R. W., Fiscus, C. L. & Holts, D. B. (1973). Stomach contents of porpoise, *Stenella* spp., and yellowfin tuna, *Thunnus albacares*, in mixed species aggregation, *Fisheries Bulletin* **71**, 1077–1092.
- Schaefer, K. M. & Oliver, C. W. (2000) Shape, volume, and resonance frequency of the swimbladder of yellowfin tuna (*Thunnus albacares*), *Fisheries Bulletin* **98**, 364–374.
- Scott, M. D. & Cattanach, K. L. (1998). Diel patterns in aggregations of pelagic dolphins and tunas in the eastern Pacific, *Marine Mammal Science* **14**, 401–428.
- Seifert, D. D. (1999) *Personal Communication*.
- Sigurdson, J. (1993) Frequency modulated whistles as a medium for communication with the bottlenose dolphin (*Tursiops truncatus*). In: H. L. Roitblat, L. M. Herman & P. E. Nachtigall (eds) *Language and Communication, Comparative Perspectives*. Lawrence Erlbaum Associates, Inc, New Jersey, pp 156–172.
- Thomas, J. A., Stoermer, M., Bowers, C., Anderson, L. & Garver, A. (1988) Detection abilities and signal characteristics of echolocating false killer whales (*Pseudorca crassidens*). In: P. E. Nachtigall & P. W. B. Moore (eds) *Animal Sonar: Processes and Performance*. Plenum Press, New York, pp 323–328.
- Wartzok, D. & Ketten, D. R. (1999) Marine Mammal Sensory Systems. In: J. E. Reynolds III & S. A. Rommel (eds) *Biology of Marine Mammals*. Smithsonian Institution Press, Herndon, Virginia. Pp. 117–175.