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CLICK CHARACTERISTICS OF NORTHERN BOTTLENOSE WHALES (*HYPEROODON AMPULLATUS*)

SASCHA K. HOOKER[1]
HAL WHITEHEAD
Department of Biology,
Dalhousie University,
Halifax, Nova Scotia B3H 4J1, Canada
E-mail: s.hooker@st-andrews.ac.uk

ABSTRACT

Sounds produced by northern bottlenose whales (*Hyperoodon ampullatus*) recorded in the Gully, a submarine canyon off Nova Scotia, consisted predominately of clicks. In 428 min of recordings no whistles were heard which could unequivocally be attributed to bottlenose whales. There were two major types of click series, initially distinguished by large differences in received amplitude. Loud clicks (produced by nearby whales socializing at the surface) were rapid, with short and variable interclick intervals (mean 0.07 sec; CV 71%). The frequency spectra of these were variable and often multimodal, with peak frequencies ranging between 2 and 22 kHz (mean 11 kHz, CV 59%). Clicks received at low amplitude (produced by distant whales, presumably foraging at depth) had more consistent interclick intervals (mean 0.40 sec, CV 12.5%), generally unimodal frequency spectra with a mean peak frequency of 24 kHz (CV 7%) and 3 dB bandwidth of 4 kHz. Echolocation interclick intervals may reflect the approximate search distance of an animal, in this case 300 m, comparable to that found for sperm whales. The relationship between click frequency and the size of object being investigated, suggests that 24 kHz would be optimal for an object of approximately 6 cm or more, consistent with the size range of their squid prey.

Key words: acoustic behavior, echolocation, frequency spectra, interclick interval, northern bottlenose whale, *Hyperoodon ampullatus.*

Very little is known of the acoustic repertoire of any of the beaked whales (family Ziphiidae). Winn *et al.* (1970) described the first recorded sounds for any species of beaked whale, recorded during a four-hour encounter with northern bottlenose whales (*Hyperoodon ampullatus*) in the Gully, a submarine canyon off Nova Scotia. This recording contained primarily single-pulse clicks

[1] Current address: Sea Mammal Research Unit, University of St. Andrews, St. Andrews, Fife, KY16 8LB, UK.

in intermittent series, but also discrete-frequency whistles, sweep-frequency chirps, and possibly also burst-pulse modulated tones. Two other studies of the acoustic behavior of free-ranging beaked whales have been opportunistically conducted on Baird's beaked whale (*Berardius bairdii*) and Arnoux's beaked whale (*Berardius arnuxii*). These species were also found to produce frequency-modulated whistles, burst-pulse clicks, and discrete clicks at times produced in quite rapid series (Dawson *et al.* 1998, Rogers and Brown 1999).

A few other sounds have been recorded from stranded beaked whales. Caldwell and Caldwell (1971) recorded pulsed chirps or whistles audible in the air from a stranded subadult male Blainville's beaked whale (*Mesoplodon densirostris*) while the animal was lying in the surf. A stranded Gervais' beaked whale (*M. europaeus*) was also found to produce clicks of variable repetition rate (Caldwell and Caldwell 1987). Bonde and O'Shea (1989) attempted to record sounds from a stranded Sowerby's beaked whale (*M. bidens*) but were unable to discern any vocalizations. Two stranded young male Hubb's beaked whales (*M. carlhubbsi*) produced pulsed sequences and whistles (Lynn and Reiss 1992). Bursts of 3–8 pulses ranged between 7 and 78 kHz, and clicks were centered at 1.77 kHz (Marten 2000).

Here we describe and discuss sounds recently recorded from northern bottlenose whales in the Gully, primarily with respect to the foraging behavior of these whales.

Methods

Acoustic recordings were made in the presence of northern bottlenose whales in the Gully, Nova Scotia (approximately 44°N, 59°W), during June–August in 1988–1990, 1995, and 1997. Whales were approached using 10–12-m sailing vessels, and recordings were made both while whales were at the surface close to the research vessel, and during the minutes after whales had left the surface. The recording equipment used consisted of a single omnidirectional hydrophone (either a Celesco LC-32 at approximately 15-m depth, 1988–1990; or Vemco VCHLF hydrophone at approximately 3-m depth, 1995 and 1997), an Ithaco 453 preamplifier, and a Nagra IV-SJ tape recorder. High-pass filters (1 kHz) in the preamplifier were used to minimize wave noise. Preliminary recordings in 1988 and 1989 were made at 19 cm/sec, but during 1989 it was discovered using a bat detector (Ultra Sound Advice, S-25, 15–200 kHz) that the whales were also making sound in the ultrasonic range (A. Faucher and H. Whitehead, personal observations). Only recordings made at 38.1 cm/sec are analyzed quantitatively here, to allow detection of ultrasonic frequencies. The frequency response of the Nagra was flat up to 40 kHz, the LC-32 hydrophone was flat at 1–80 kHz, and the VCHLF hydrophone was flat at 1–25 kHz and rolled off to 35 kHz (frequencies up to 35 kHz would have been detected although with reduced sensitivity). Therefore, in 1989 and 1990 our recording system could detect sounds up to approximately 40 kHz (the response of the Nagra), whereas in 1995 and 1997 our recording system was limited by the VCHLF hydrophone which could detect sounds up to 35 kHz.

To maximize the likelihood that recordings were of bottlenose whales, tape segments were selected for which there had been no dolphins or other toothed whales sighted within an hour before or after the recording. Signals from these tapes were played at half speed, and were viewed using a Multigon Industries Uniscan II spectrum analyzer. From these, sixteen tape segments with high signal to noise ratio and for which either only one or very few whales were vocalizing at one time were chosen for more detailed analysis. Ten click sequences from each segment (selected such that there was the least ambiguity that clicks were from the same animal) with at least 10 sec between each were digitized at 8 bits and analyzed using the software Canary 1.1. To avoid aliasing, a Krohn-Hite Band-Pass Filter (Model 330N, Krohn-Hite, Cambridge, MA) was used. Tapes were played at ⅛ speed (4.75 cm/sec) with a computer sampling rate of 44 kHz.

Audio (based on amplitude and frequency) and visual (based on the amplitude of the waveform) cues were used to identify clicks from the same animal. The interclick interval was defined as the time between the maximum amplitude of the first pulse of the first click to the maximum amplitude of the first pulse of the next click. The duration of the click was determined from the onset of the click to the point at which the signal decayed to the level of noise. A click quality value was assigned such that high-quality clicks were those of high signal-to-noise ratio with relatively simple spectral characteristics (more likely to represent signals recorded from directly ahead of the vocalizing whale, Au 1993). The frequency spectrum (amplitude *vs.* frequency) was calculated for each high-quality click. The region of the waveform over the duration of the click was used to calculate its quadratic spectrum (4,096 point FFT, frame length 4,096 pt, time frame 16 pt, Hamming window, frequency resolution 5.4 Hz). The peak frequency, 3 dB bandwidth, the number of peaks and the secondary peak frequency (if maximum energy of this was greater than one-third that of the first peak frequency) were noted. The majority of clicks were observed to have a multiple pulse structure, the second and consecutive pulses of which appeared to be reflections of the first, presumably on account of the shallow hydrophone depth and/or the proximity of the research vessel to the hydrophone (Fig. 1). All measurements were made using only the first pulse of each click.

Results

In total, 428 min of tapes containing bottlenose whale sounds were preliminarily investigated. No whistles were heard in these recordings which could be unequivocally attributed to bottlenose whales. Although distant whistles were heard, these were generally within an hour of a dolphin sighting, and no whistles were heard that even approached the amplitude heard concurrently for bottlenose whale clicks.

Two classes of click series were distinguished by their distinctly different

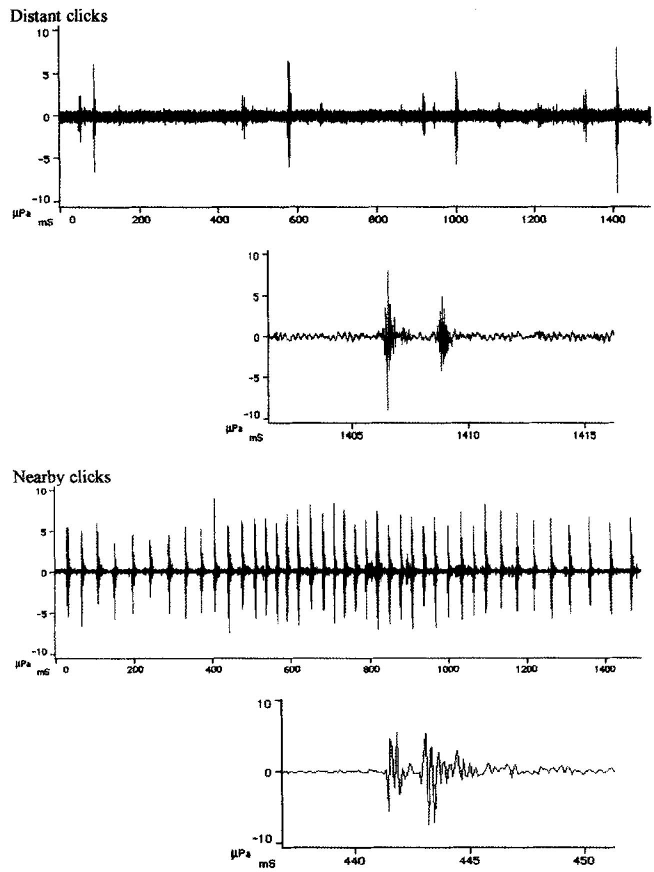


Figure 1. Example waveforms showing difference between deep-water and surface clicks. Expanded plots show echoes often associated with each click.

amplitudes. The magnitude of this difference was great enough that clicks could be categorized to type without ambiguity. The first class (hereafter termed "deep-water" clicks) was heard at low amplitude, and was heard at times when whales were not at the surface. The second class (hereafter termed "surface" clicks) was heard at much greater amplitude, often while whales were at the surface near the research vessel (Table 1). Deep-water clicks tended to be very regular (*i.e.,* low coefficient of variation) in interclick interval (Table 2, Fig. 1). Surface clicks were often emitted in rapid succession in the form of "click trains," often speeding up and then slowing and stopping over periods of 20 sec or more (Fig. 2).

These two click types were significantly different in their interclick intervals (ANOVA including tape segment as a main effect, $F_{1,144} = 39.5$, $P < 0.001$; Table 2, Fig. 3). Surface clicks had significantly different interclick intervals between recording sessions, but deep-water interclick intervals did not differ

Table 1. Recording sequence details, shows co-ordination between occurrence of clicks thought to be produced in deep-water with diving behavior.

Tape	Date	Local time	Behavior	Deep-water	Surface	# Whales
S27	11/08/89	1515–1518	diving	√		4 (then 2)
S28	11/08/89	1936–1942	milling at surface		√	5 (6)
S30	11/08/89	2032–2036	some at surface	√		5
S31	11/08/89	2051–2057	at surface (5 m away)		√	3
S34	12/08/89	1514–1519	diving	√		— (2)
X10	06/07/90	1536–1544	surface/diving	√		2 (then 4)
X11	06/07/90	1546–1549	surface/diving		√	2 (4)
X17	07/07/90	1739–1744	diving (some at surface)	√	√	4 (5)
X31	30/07/90	0904–0912	surface		√	3 (7)
X44	08/07/90	1256–1259	surface		√	2 (9)
BB1	29/08/95	1730–1735	long dive	√		— (4)
T2	12/06/97	0959–1003	diving	√		— (2)
T3	16/06/97	1102–1104	diving	√		— (then 3)
T3	16/06/97	1109–1110	at surface (10 m away)		√	3
T4	07/07/97	1154–1156	diving	√		— (3)

Note: # whales—number given is number of whales at the surface at the time of recording, number in parentheses is the total number of whales present.

Table 2. Characteristics of click types. Mean (SD) shown for high quality clicks for each recording session. Grand mean (of sessions) shown below, SD shows variability between sessions. (Each session probably contains replicates of one or more individuals.)

Tape	# High-quality clicks	Interclick interval(s)	Duration (msec)	Peak frequency (kHz)	3dB bandwidth (kHz)
Deep-water					
S27	9	0.46 (0.08)	0.34 (0.08)	24.97 (0.98)	4.16 (0.81)
X34	8	0.41 (0.08)	0.32 (0.03)	25.19 (0.93)	4.73 (0.88)
X10	5	0.43 (0.10)	0.50 (0.41)	20.86 (5.97)	3.41 (1.46)
X17	9	0.45 (0.05)	0.34 (004)	22.36 (0.68)	4.96 (0.53)
BB1	7	0.43 (0.10)	0.37 (0.10)	22.80 (0.99)	3.93 (0.64)
T2	3	0.33 (0.04)	0.30 (0.05)	23.97 (0.23)	4.32 (0.81)
T4	6	0.33 (0.10)	0.36 (0.05)	25.50 (1.12)	3.99 (0.34)
T3	5	0.38 (0.02)	0.28 (005)	25.37 (021)	4.29 (0.09)
Overall		0.40 (0.05)	0.35 (0.07)	23.88 (1.71)	4.23 (0.48)
Surface					
T3	2	0.02 (0.01)	3.32 (2.18)	4.36 (2.52)	0.44 (0.33)
S28	5	0.05 (0.02)	0.51 (0.29)	21.32 (5.07)	3.91 (3.08)
S31	7	0.04 (0.03)	0.56 (0.15)	16.07 (4.07)	2.74 (1.13)
X44	3	0.03 (0.01)	2.52 (0.96)	4.77 (2.95)	0.49 (0.07)
X17	4	0.14 (0.04)	0.49 (0.07)	13.30 (4.61)	2.72 (0.66)
X11	7	0.13 (0.10)	6.08 (9.40)	6.73 (4.68)	2.19 (0.72)
X31	9	0.06 (0.01)	0.63 (0.12)	9.00 (4.71)	3.25 (1.00)
Overall		0.07 (0.05)	2.02 (2.13)	10.79 (6.36)	2.25 (1.33)

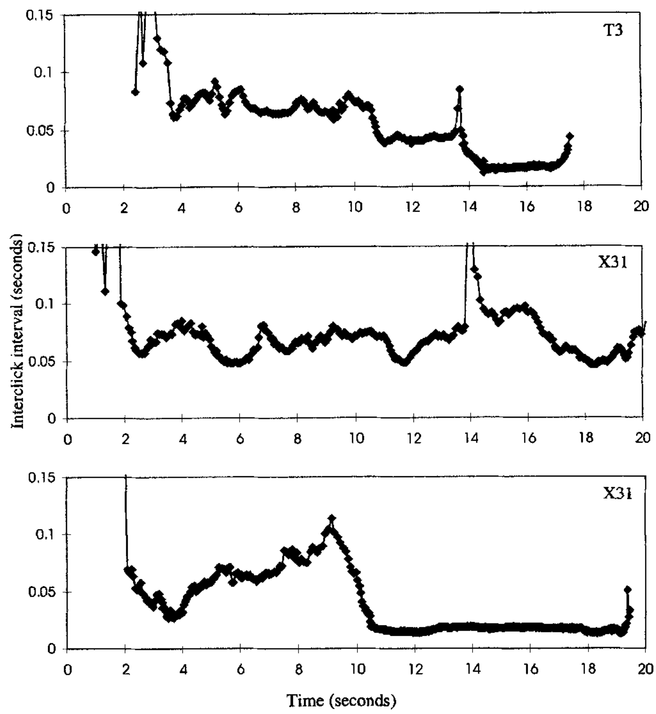
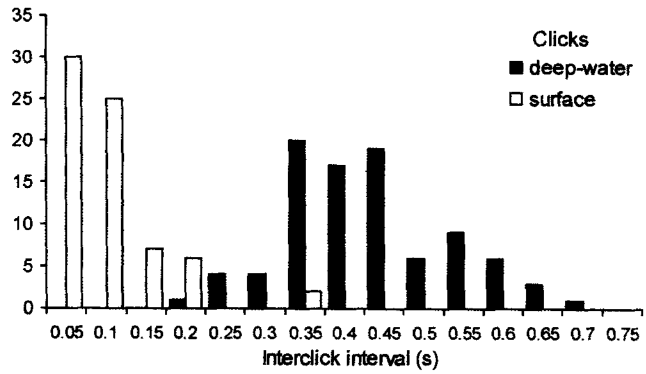


Figure 2. Examples of sequential temporal variation in interclick intervals during three series of surface clicks. Sessions during which recordings were made are shown (see Table 2).

significantly between recording sessions (surface clicks: ANOVA $F_{6,63} = 2.55$, $P = 0.029$; deep-water clicks: ANOVA $F_{8,81} = 1.81$, $P = 0.087$).

Click duration was not significantly different between click types (ANOVA including tape segment as a main effect, $F_{1,72} = 0.27$, $P = 0.6$). There were also no significant differences between mean click durations from different recording sessions (ANOVA, deep-water clicks $F_{7,42} = 1.04$, $P = 0.42$; surface clicks $F_{6,30} = 1.60$, $P = 0.18$). However, variability of surface click durations was much greater than that of deep-water clicks (CV 105 % cf. CV 20 %; Table 2). Click duration was significantly negatively correlated with primary click frequency; clicks of increased duration tended to be of lower frequency (Pearson correlation, $r = 0.38$, $P < 0.001$).

The peak frequencies of clicks when whales were at the surface were significantly different from those when they were generated at depth (Fig. 3; ANOVA including tape segment as a categorical variable, $F_{1,72} = 65.02$, $P < 0.001$). The frequency of deep-water clicks was more consistent (21–25 kHz) than that of surface clicks (4–21 kHz), but frequency varied significantly with tape segment for both click types (ANOVAs: deep-water clicks, $F_{7,42} = 4.223$, $P = 0.001$; surface clicks, $F_{6,30} = 9.15$, $P < 0.001$; Fig. 4). A higher proportion of deep-water clicks (84%) than surface clicks (57%) were unimodal in frequency.



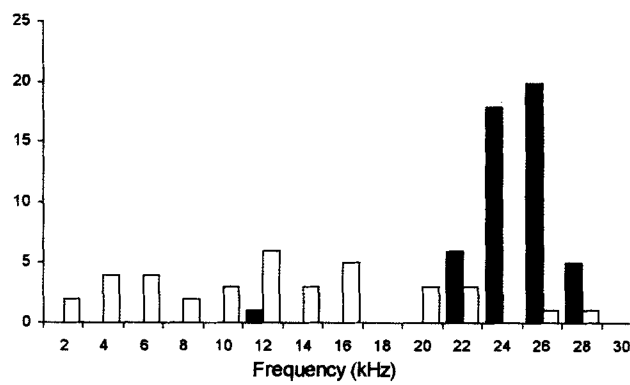


Figure 3. Frequency histograms showing (top) interclick intervals and (bottom) peak frequencies of deep-water and surface clicks. Interclick intervals (n = 160) are shown for all clicks regardless of quality. Peak frequencies shown only for high quality clicks (n = 87), since frequency appeared to be affected by click quality.

Discussion

Although sounds produced by bottlenose whales during an opportunistic encounter have previously been reported (Winn *et al.* 1970), this study provides a more comprehensive dataset with which to examine the acoustic behavior of this species. The recordings by Winn *et al.* (1970) were primarily made while whales were at the surface near their research vessel, and during their 4-h encounter they recorded whistles of 0.115–0.85-sec duration between 3–16 kHz, some at a single frequency and others (described as sweep frequency chirps) ranging through frequencies, together with burst pulse (modulated) tones. However, in the recordings described here, no whistles were heard which could be ascribed with certainty to bottlenose whales. Although whistles were heard during several recordings, these were generally of low amplitude, and appeared similar to sounds produced by dolphins (typically Atlantic white-sided dolphins, *Lagenorhynchus acutus,* or common dolphins, *Delphinus delphis*), or longfinned pilot whales (*Globicephala melas*) which were often sighted within

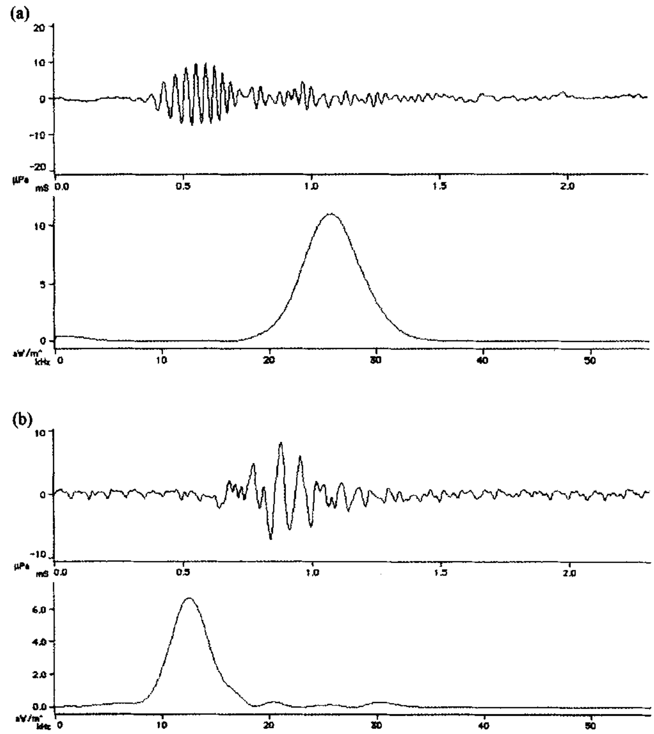


Figure 4. Examples of waveform and frequency spectrum of a good quality deep-water click (a) and a surface click (b).

half an hour of the recording. Winn *et al.*'s (1970) recording was made in a similar situation: they noted that they were following pilot whales when they found a group of bottlenose whales and that the pilot whales continued out of range of the recording system. The frequency of whistles they recorded (primarily 3–6 kHz; see their fig. 1) are in fact similar to those described for longfinned pilot whales (Weilgart and Whitehead 1990). However, more recordings during which no other animals are vocalizing will be required before it can be stated with certainty that bottlenose whales do not produce whistles.

Clicks classified as "surface" in this study were similar to those documented by Winn *et al.* (1970) as possible burst-pulse tones (compare their fig. 3 with Fig. 1 of this study), but they did not record any clicks similar to the deep-water clicks observed in this study. This may have been because their analysis focused on the loudest whales, *i.e.*, those nearby rather than any at depth.

Assuming that such clicks are for echolocation, the interclick interval and frequency of clicks recorded are used to infer information on the size of prey and the ranges over which foraging takes place (*cf.* Goold and Jones 1995 for sperm whales, *Physeter macrocephalus*). The interclick interval of 0.4 sec (*i.e.*, 2.5 sec^{-1}) found for deep-water clicks of northern bottlenose whales is slightly faster than the click rates of 0.5–2 sec^{-1} of sperm whales (Backus and Schevill

1966, Whitehead and Weilgart 1990, Goold and Jones 1995, Møhl *et al.* 2000). Both sperm whales and northern bottlenose whales are teuthivorous deep divers (Rice 1989, Watkins *et al.* 1993, Hooker and Baird 1999), so their foraging behavior is likely to be similar. The interclick interval is thought to depend principally on the range at which searching is taking place or the distance of the object on which an animal is echolocating, since animals wait for the return of an echo before the next click is emitted (Au 1993). The interclick interval of 0.4 sec would thus correspond to a range of 300 m, reflecting the likely distance over which searching takes place (speed of sound in water ~1,500 $msec^{-1}$). The mean interclick interval of surface clicks (0.07 sec) corresponds to a distance of 52 m. This approximately reflects the distance whales were from the research vessel when these sounds were recorded, suggesting that these sounds may have been directed at the research vessel. However, the variability of click rates from surface whales (Fig. 2) does not appear to match the hypothesis that these whales were simply echolocating on the research vessel.

The average peak frequency of northern bottlenose whale clicks recorded while whales were at depth was 24 kHz (Table 2). This is much higher than the frequencies of sperm whale clicks, for which Goold and Jones (1995) found that males used peak frequencies at 400 Hz and 2 kHz and females used frequencies at 1.2 and 3 kHz. The higher frequencies of northern bottlenose whales are more similar to frequencies (22–25, 35–45, and some 80+ kHz) found for Baird's beaked whale (Dawson *et al.* 1998). However, we cannot comment on the likelihood of high-frequency (greater than 35 kHz) components in bottlenose whale clicks due to the frequency limitations of our sampling system.

The strongest echoes are returned by a target when it is of a size comparable to, or larger, than the wavelength of sound reaching it (Fletcher 1992). A frequency of 24 kHz is optimal for a target size of greater than or equal to 6.25 cm (v(water) = 1,500 $msec^{-1}$; $v = f\lambda$, $\lambda = 1{,}500/24{,}000$). Northern bottlenose whales in the Gully are thought to feed predominately on the squid *Gonatus steenstrupi* (Hooker 1999, Hooker *et al.* 2001). *G. steenstrupi* tend to have mantle lengths up to approximately 10 cm (Kristensen 1981). This fits with the implication from click frequencies that bottlenose whales are searching acoustically for objects of approximately >6 cm in size. The reflective structures within the squid are likely the beak and the pen, the latter reaching over 6 cm in length, although the beak is only approximately 1 cm in size. *Gonatus* spp. are also noted for the high fat content of the liver (Clarke *et al.* 1985), which may help present a good acoustic reflection. A fairly constant rate of clicking was heard for deep-water clicks which is probably indicative of the search strategy of these whales. We have conducted detailed analysis of only small portions of the entire acoustic data set, however, and so it is quite likely that we would not have detected prey capture events in this record. Thus, we are unable to draw further conclusions regarding the feeding mechanism of these whales. There is some debate as to the extent to which other deep-diving species use vision for prey capture. It is unlikely that downwelling light reaches the depths at which bottlenose whales forage (over 800 m, Hooker and Baird 1999). Bioluminescence is found among many deepwater (400–1,200 m) squid, and is especially common in oegopsid squid (suborder Oegopsina), including the genus *Gonatus* (Hanlon and Messenger 1996), although photophores have not been noted on *Gonatus steenstrupi* (Kristensen 1981).

The difference in frequencies of clicks at the surface to those at depth appears unusual, compared to what is known of the acoustic behavior of other cetaceans. In fact, we would expect some reduction in received high-frequency components of clicks generated at depth, due to the increased absorption distance and poor transmission of high frequencies in the sea. There appears to be little documentation available concerning changing frequency according to behavior in cetaceans. Dawson (1991) described changing characteristics of click-frequency spectra with different behaviors for Hector's dolphin (*Cephalorhynchus hectori*), although these dolphins changed the number of peak frequencies within the main frequency range, rather than the primary frequency range itself. Belugas (*Delphinapterus leucas*) shift their clicks to higher frequencies and intensities when moved to a noisier environment (Au *et al.* 1985). It is thought that higher frequencies may be an effect of producing more intense sounds (Au *et al.* 1985). It is therefore possible that bottlenose whales produce higher-frequency sounds at depth as a correlate of the generation of higher-intensity clicks.

Among odontocetes, the melon is thought to focus the echolocation clicks produced. Bottlenose whales have a fat body (analagous to the melon) which lies between two maxillary crests (Heyning 1989). In adult male bottlenose whales these maxillary crests become much enlarged, and the fat body becomes more fibrous in nature (Heyning 1989, Mead 1989). It is unclear whether the differences in facial anatomy between mature male bottlenose whales and females or juveniles would affect the sound produced. Differences in click characteristics observed in different tape segments may indicate individual differences, but further work cataloging sounds of different age-sex classes is needed before it is clear whether different age-sex classes produce different sounds.

The bandwidth of the recording systems used in this study limited analysis to sounds below 35 kHz. Further work, using wide-band recordings is required to determine whether there is appreciable energy at higher frequencies. However, although the full acoustic repertoire of this species remains unknown, this study demonstrates that bottlenose whales are producing sound within the 2–26 kHz range. The sounds produced by whales at depth appear to show the frequency and patterning expected for the generation of high-intensity clicks used in foraging on squid.

Acknowledgments

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