Echolocation clicks of free-ranging Chilean dolphins (*Cephalorhynchus eutropia*) (L)

Thomas Götz,[a] Ricardo Antunes, and Sonja Heinrich
Sea Mammal Research Unit, Scottish Oceans Institute, University of St. Andrews, St. Andrews KY16 8LB, United Kingdom

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In this paper, evidence is provided that Chilean dolphins *(Cephalorhynchus eutropia)* produce ultrasonic echolocation clicks of the narrow-band high-frequency category. Echolocation clicks emitted during approaches of the hydrophones consisted only of narrow-band (rms-BW: 12.0 kHz) single pulses with mean centroid frequencies of about 126 kHz, peak frequencies of 126 kHz, and a 20 dB duration of 82.6 μs. The maximum received level measured exceeded 165 dB re 1 μPa. In addition, high repetition-rate buzzes were recorded during foraging behavior (click interval: 2 ms), but no whistles or calls with tonal components were detected.
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I. INTRODUCTION

Delphinid echolocation signals can be classed into two broad categories. Whistling dolphins produce short (40–50 μs) broadband signals with spectral peaks at about 40 and/or 120 kHz (Au, 2000). Nonwhistling dolphins of the genus *Cephalorhynchus* use longer duration, narrowband, high-frequency (NBHF) clicks (Au, 2000). Hypotheses proposed for the evolution of NBHF signals include adaptations to the use of a low ambient noise window (Madsen 2005) and avoidance of predation from killer whales (*Orcinus orca*) (Morisaka and Connor, 2007). To date, NBHF clicks in dolphins have only been documented in four members of the genus *Cephalorhynchus* Kamminga and Wiersma, 1982, Dawson and Thorpe, 1990, Kyhn *et al.*, 2009, Kyhn *et al.*, 2010). A complete picture of all congeners is required to better understand the evolutionary and ecological factors shaping odontocete clicks. We provide the first characterization of echolocation clicks of C. eutropia, a poorly known delphinid endemic to the shallow near shore waters of southern Chile

II. METHODS

A. Field site and recording equipment

Sounds of free ranging *C. Eutropia* were recorded from single species groups of three to six dolphins off Isla Chiloe (43° S, 73° W) in southern Chile over four days in February 2005 and January 2008. All recordings were obtained in calm seas (Beaufort scale 1–2) when the dolphins were milling or foraging within 20–40 m of a drifting 4 m inflatable boat. On one occasion in 2005 clicks were recorded from a single dolphin, and consecutively a group of four dolphins approaching the hydrophone head on to within 1 m distance. In 2005 recordings were made using a Brüel & Kjær 8103 hydrophone with a B&K 2635 charge amplifier connected to a high-speed data acquisition card (National Instruments DAQ A1-16E, 12 bit resolution, 500 kHz sampling rate). In 2008 a two element hydrophone array was used. The array consisted of a calibrated Reson TC-4013 hydrophone connected to a custom-built amplifier (measured voltage gain 20 dB) and a B&K 8105 hydrophone connected to a B&K 2635 charge amplifier. The frequency response of the custom-built preamplifier was flat (less than ± 0.5 dB) up to 150 kHz. Both hydrophones had a maximum variation in their sensitivity of about ± 2 dB at frequencies between 100 and 150 kHz. The output from both amplifiers was recorded on two channels of a data acquisition card (National Instruments USB-6251 BNC, 16 bit resolution, 500 kHz sampling rate per channel).

B. Click selection criteria and sample size

Due to the directionality of the clicks, we selected a subsample of potential on-axis signals for detailed click analysis. This subsample was obtained by assigning all clicks to distinct click trains defined as a series of clicks that started at low amplitudes and consecutively reached a local maximum with the click interval being either constant or changing continuously. From each click train, we selected only those clicks with the highest received level resulting in a subsample of 83 clicks. Clicks recorded in 2008 were always selected from the channel at which the signal was recorded at a higher received level. We report these "selected clicks" from both years as "potential on-axis clicks." We also provide parameters for all other clicks labeled as "remaining or off-axis clicks" (n=761). The 2005 recordings also contained two echolocation buzzes of foraging dolphins. We defined a buzz as a rapid series of clicks emitted at intervals of less than 5 ms which were preceded by click intervals of 15 ms or more.

C. Click processing

Click structure was analyzed using custom-written routines in MATLAB 6.5 (the Mathworks Inc., Natick, MA).

[a]Author to whom correspondence should be addressed. Electronic mail: tg45@st-andrews.ac.uk.

Clicks were selected from background noise by using a 20 dB criterion, i.e., the part of the signal between the −20 dB power points on the envelope was selected for analysis. The duration of the signal was therefore defined as the time delay between the −20 dB power points on the envelope. We also tested the signal duration based on selecting 98% of the energy of the signal as suggested by Madsen *et al.* (2004) . However, we discarded this energy criterion as we found that it would select large tails of echoes after the primary pulse, which were most likely not produced by the animal (e.g., Li *et al.* 2005). No clicks with a signal to noise ratio of less than 20 dB were included in the analysis. The spectral characteristics of the clicks were calculated on the selected part of the signal using a fast Fourier transformation (1024 steps, rectangular window) with zero padding to fill the gaps around the actual signal. Peak frequency was defined as the frequency with maximum amplitude in the power spectrum. The 3 dB bandwidth represents the frequency width between the half power points (3 dB down from the maximum peak) of the power spectrum (*sensu* Au, 1993).

The centroid-frequency, rms duration, rms bandwidth, time-bandwidth product, and time centroid, were calculated using equations given in Au, (1993). The centroid frequency divides the power spectrum in two equal parts. Similarly, the time centroid is the point in time that divides the envelope of the signal in two equal parts. The instantaneous frequency at the maximum pressure point was calculated from the phase information obtained from a Hilbert transformation of the signal. Instantaneous frequencies were plotted over time in order to assess subtle changes in frequency over the course of the signal. The $Q_{3\ \mathrm{dB}}$ values were defined as the centroid frequency divided by the 3 dB bandwidth.

Received levels were calculated from measured signal voltage after compensating for the gain in the instrumentation chain and using the known transducer sensitivity.

III. RESULTS

All recorded sounds were short ultrasonic clicks with no energy below 50 kHz. No whistlelike or tonal calls were detected in any of the recordings. Signal parameters calculated for the "potential on-axis clicks" and all "remaining (off-axis) clicks" are summarized in Table I.

A. Potential on-axis clicks

The two clicks with the highest received level selected from click trains with a high signal to noise ratio were more likely to have originated from the center of the transmission beam (on-axis) than the remaining data set. These potential on-axis signals were short (mean 20 dB duration 82.6 μs) narrow-band (rms bandwidth 12 kHz, 10 dB bandwidth 33.6 kHz) signals with a mean center frequency of about 126 kHz [Figs. 1(a)–1(c); Table I]. Clicks had a rms duration of 14.2 μs. Potential on-axis clicks showed a relatively symmetric energy distribution in the power spectrum with the average peak (126.3 kHz) and centroid frequency (126.2 kHz) being nearly identical (Fig. 1). Instantaneous frequencies tracked over consecutive cycles of the signal revealed a nearly constant-frequency characteristic of the click [Fig. 1(b)]. The average instantaneous frequency at the maximum pressure point was 125.1 kHz, almost the same as the center frequency. The mean 3 dB bandwidth (17.9 kHz) was higher than the rms bandwidth (12.0 kHz). The average time-bandwidth product was 0.16 and average $Q_{-3\ \mathrm{dB}}$ value of 7.8 reflected the narrow bandwidth of the signals.

TABLE I. Acoustic characteristics of potential "on-axis" and likely "off-axis" clicks of *C. eutropia* recorded in 2005 and 2008.

Click type	Potential "on-axis" clicks	Remaining ("off-axis") clicks
Click selection	Two clicks with highest received level per click train	None
Mean ± SD		
	n=83	n=761
Centroid freq. (kHz)	126.2 ± 2.0	127.1 ± 3.2
Peak frequency (kHz)	126.3 ± 2.3	126.6. ± 3.8
Inst. freq. (kHz)	125.1 ± 3.6	127.5 ± 5.5
20 dB duration (μs)	82.6 ± 30.4	113.1 ± 57.0
rms duration (μs)	14.2 ± 5.9	23.2 ± 15.2
3 dB bandwidth (kHz)	17.9 ± 4.9	15.2 ± 7.2
10 dB bandwidth (kHz)	33.6 ± 8.1	32.1 ± 12.3
rms bandwidth (kHz)	12.0 ± 2.4	12.4 ± 3.5
Time centroid (kHz)	33.7 ± 11.9	46.4 ± 20.7
$Q_{3\ \mathrm{dB}}$	7.8 ± 3.0	10.8 ± 6.3
Time-bandwidth product	0.16 ± 0.07	0.27 ± 0.18

B. Remaining (off-axis) clicks

Potential on-axis clicks and all remaining (off-axis) clicks showed very similar peak and centroid frequencies (Fig. 1, Table I). However, off-axis clicks differed with respect to their temporal characteristics from the potential on-axis clicks. Off-axis clicks had longer 20 dB durations (113.1 μs), and the rms duration was almost twice as long as for potential on-axis clicks (23.2 μs) [Fig. 1(d), Table I]. Many remaining off-axis clicks had long tails, i.e., a series of local amplitude maxima immediately following the first pulse. Some clicks were also found to be double pulses [Fig. 1(d)] with more or less equal amplitude. These double pulses either occurred as two consecutive pulses or as two pulses apparently merged together into one click with two local amplitude maxima [Fig. 1(d)].

C. Buzz clicks

Since the sample set is very small (n=10 clicks, 2 buzzes), this description must be considered preliminary. The minimum click interval during echolocation buzzes was 1.5 ms. Clicks emitted at pulse intervals of less than 5 ms (buzz) were shorter (mean 20 dB duration ±SD: 42.0 ± 17.4 μs) while the rms bandwidth (28.8 ± 9.3 kHz) and 3 dB bandwidth (34.5 ± 10.9) was approximately twice as high as in all other recorded clicks (Table I). Centroid (100 kHz ± 14.4), peak (96.6 ± 34.3), and instantaneous frequencies

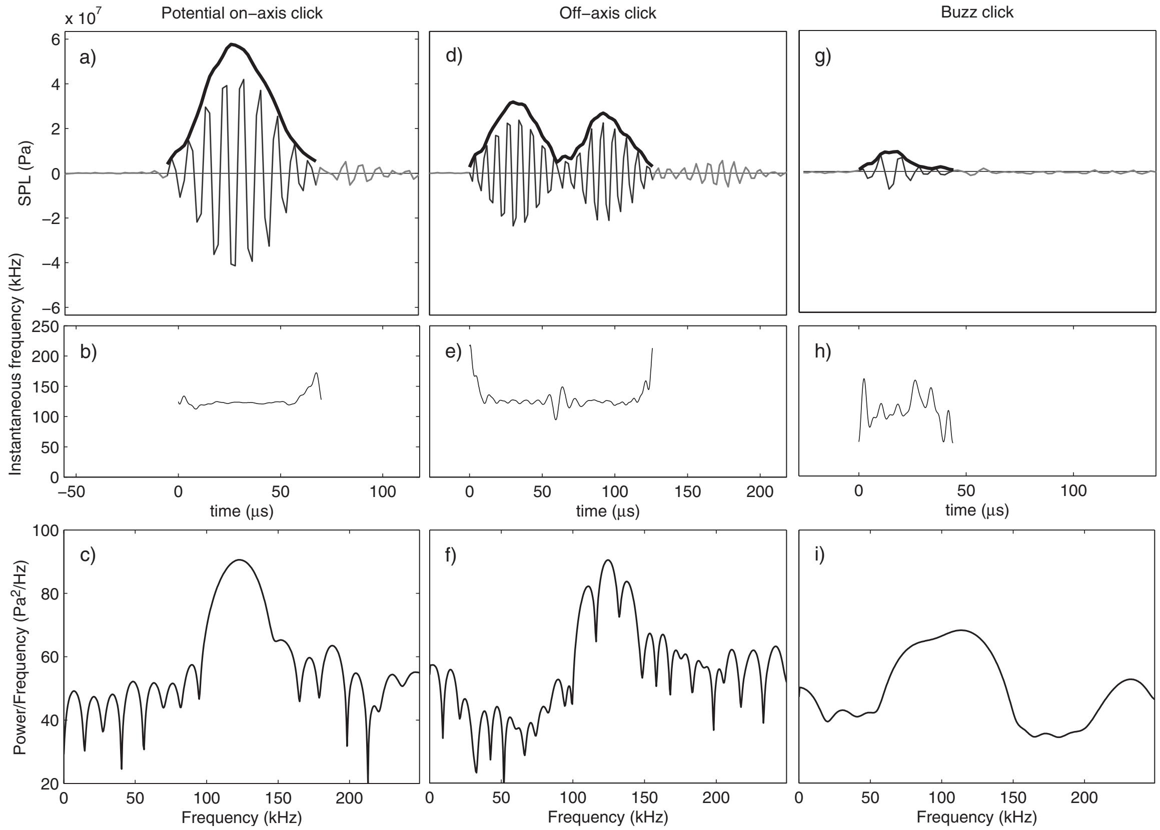

FIG. 1. Waveform, instantaneous frequency over time and power spectrum for a representative potential on-axis click [(a)–(c)], an off-axis click ([d)–(f)], and a buzz click. The envelope of the signal in the waveform display indicates the analysis window, i.e., the part of the click selected by the 20 dB criterion. Likely "off-axis" clicks frequently consisted of merged double pulses (d).

(102 kHz ± 10 kHz) were lower than in echolocation clicks emitted at higher click intervals. The $Q_{3\ \mathrm{dB}}$ of 2.6(±1) reflects the higher bandwidth of these clicks.

D. Received levels

Measured peak to peak received levels ranged from 140 to 165 dB re 1 μPa. The highest recorded received level was 165 dB re 1 μPa during a close hydrophone approach recorded in 2005. All buzz clicks were recorded at received levels below 145 dB re 1 μPa.

IV. DISCUSSION

A. Click parameters

We only recorded narrowband ultrasonic pulses but no whistlelike sounds or calls with tonal components. The main parameters of clicks recorded from *C. eutropia* closely resemble those of its congeners. Clicks of Commerson's dolphin (*C. commersonii)* have peak frequencies of approximately 130 kHz (Dziedzic and Debuffrenil, 1989) and a duration ranging from 350 to 500 μs . Dawson and Thorpe (1990) described vocalizations of Hector's dolphins (*C. hectori)* to be short narrowband ultrasonic clicks with peak frequencies ranging from 115 to 135 kHz but with considerable variation in pulse length ranging from 100 to 600 μs (average 137 μs). Kyhn *et al.* (2009) reported *C. hectori* to emit clicks at similar frequencies (129 kHz) but found shorter pulse length (10 dB duration: 57 μs) than previously reported. Signals of C. *eutropia* in this study also closely resemble those produced by harbor porpoises (*Phocoena phocoena*). Madsen *et al.* (2005) reported similar 3 dB bandwidths for a variety of *odontocetes* in the NBHF category, such as *P. phocoena* (6 kHz), pygmy sperm whales (*K. breviceps*) (7 kHz), and *C. hectori* (14 kHz), which are similar to our value of 17.9 KHz for *C. eutropia*. Au (1993) reported rms bandwidths ranging from 16 to 26 kHZ and rms durations between 19 and 26 μs for and two *Phocoenid*and two *Cephalorhynchus* species. While the bandwidth values for these species are similar to *C. eutropia*, our potential on-axis clicks are much shorter (14.2 μs). However, off-axis clicks in our study had similar rms durations (23.2 μs).

In conclusion, most frequency parameters for NBHF species seem to be consistent across studies and species. There is, however, considerable variation of click duration and time-domain parameters [e.g., double and multipulses as in Fig. 1(d)] across various studies and within our recordings. Our potential on-axis signals closely resemble the relatively short clicks described in the study by Kyhn *et al.* (2009). Li *et al.* (2005) showed that hydrophones deployed around a group of finless porpoises (*Neophocaena neophocaenoides*) recorded interclick interval (ICI) patterns which suggest that multipulses and "tails of secondary pulses" resulted from surface and bottom reflections. While this may partly explain the phenomenon, our data show double pulses are frequently merged. Thus, in some cases where ICIs are very short, click characteristics may result from off-axis distortion, internal reflections, or the presence of two signal generators in the animal's head. The latter has been shown for Beluga (*Delphinapterus leucas*) in a study where the sound field was mapped around the test subject's head (Lammers and Castellote, 2009). When recordings were made on the acoustic axis of beluga clicks, only a single pulse appeared (compare to our "potential on-axis clicks"), but two pulses emerged for recordings made in the periphery of the sonar beam [see Fig. 1(d)].

The click with the highest received level (of 165 dB re 1 μPa) showed minimal signs of clipping and originated from a dolphin approaching the hydrophone head on. Thus, our highest received level for *C. eutropia* compares well to backcalculated source levels of 177 dB re 1 μPa reported for *C. hectori* (Kyhn *et al.*, 2009).

B. Buzz clicks

C. eutropia clicks which were produced in high repetition-rate echolocation buzzes (click intervals <5 ms) had a higher bandwidth and shorter duration compared to regular echolocation clicks. The 3 dB bandwidth of 40 kHz for *C. eutropia* buzz clicks was similar to that of species producing broadband clicks (e.g., *Tursiops*) but did not resemble the NBHF signal category (compare Madsen *et al.*, 2005). Since we only selected buzz clicks with a signal to noise ratio higher than 20 dB, the difference cannot be explained by ambient noise being selected within the analysis window [e.g., Fig. 1(g)]. The shorter duration might result from buzz clicks having relatively low received levels, and thus the analyzed part of the signal only reflected the "top" of the real waveform with the rest of the signal vanishing in the background noise. However, average instantaneous frequencies at maximum pressure were also lower in buzz clicks (102 kHz ± 10 kHz). Hence, if the differences in buzz clicks are not artifacts, then this signal type might be adapted to a target classification and localization task immediately before prey capture. The use of signals with higher bandwidth could decrease the uncertainty of range estimation (Au, 1993) and might serve to improve target localization before prey capture. Further studies using more sophisticated recording equipment would be needed to confirm our preliminary observations.

C. Implications for passive acoustic monitoring

Clicks closely resembled the typical NBHF sonar signals, thus making *C. eutropia* easily distinguishable from all other *delphinid* species producing broadband clicks. However, distributional ranges of *C. eutropia* overlap with those of two other NBHF species (*L. australis* and *P. spninipinnis*), although there is some indication for small-scale habitat partitioning among the three species (Heinrich, 2006). The co-occurrence of potentially three NBHF species poses additional challenges for acoustic species discrimination. Soldevilla *et al.* (2008) succeeded in developing algorithms that could distinguish signals from two species of *delphinids* with broad-band clicks by quantifying spectral peaks and notch pattern of recorded off-axis clicks. We therefore believe that it is valuable not only to report source parameters of clicks (potential on-axis clicks) but also off-axis clicks as they are "likely to be recorded at sea" [see Fig. 1(d), Table I].

V. CONCLUSIONS

We have provided the first sound characterization of *C. eutropia* and showed that they produce NBHF clicks similar to those of their congeners and the *Phocoenid* family. Clicks recorded on the acoustic axis appeared to be shorter and largely consisted of single pulses, while off-axis clicks were longer in duration and showed a pattern of amplitude modulation or double pulses.

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