Comparison of echolocation clicks from geographically sympatric killer whales and long-finned pilot whales (L)

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The source characteristics of biosonar signals from sympatric killer whales and long-finned pilot whales in a Norwegian fjord were compared. A total of 137 pilot whale and more than 2000 killer whale echolocation clicks were recorded using a linear four-hydrophone array. Of these, 20 pilot whale clicks and 28 killer whale clicks were categorized as being recorded on-axis. The clicks of pilot whales had a mean apparent source level of 196 dB re 1 μPa pp and those of killer whales 203 dB re 1 μPa pp. The duration of pilot whale clicks was significantly shorter (23 μs, S.E. = 1.3) and the centroid frequency significantly higher (55 kHz, S.E. = 2.1) than killer whale clicks (duration: 41 μs, S.E. = 2.6; centroid frequency: 32 kHz, S.E. = 1.5). The rate of increase in the accumulated energy as a function of time also differed between clicks from the two species. The differences in duration, frequency, and energy distribution may have a potential to allow for the distinction between pilot and killer whale clicks when using automated detection routines for acoustic monitoring.
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I. INTRODUCTION

Killer whales (*Orcinus orca*) and long-finned pilot whales (*Globicephala melas*) are the largest members of the family Delphinidae. In Northern Norwegian waters the two species overlap in their geographical distribution (Bloch *et al*., 2003; Carwardine, 2000). Killer whales are generally considered to be relatively shallow divers with a reported maximum dive depth of 260 m for a trained animal (Bowers and Henderson, 1972). This species feed on a broad variety of prey ranging from small fish to baleen whales (Ford *et al*., 1998). Norwegian killer whales herd their preferred prey herring (*Clupea harengus*) into tight schools at the surface where the whales perform underwater tail-slaps paralyzing the fish, thereby making them easier to catch (Domenici *et al*., 2000; Similä and Ugarte, 1993; Simon *et al*., 2005, 2006). In contrast, the main prey items for North Atlantic pilot whales are mesopelagic cephalopods (Desportes and Mouritsen, 1993). Pilot whales are relatively deep divers, diving to depths of more than 800 m (Heide-Jørgensen *et al*., 2002). Killer whale echolocation clicks are broadband signals with a center frequency of 22–80 kHz, a duration ranging from 30 to 200 μs, and a source level of 173–224 dB re 1 μPa at 1 m (Au *et al*., 2004, Simon *et al*., 2007). The source properties of echolocation clicks from pilot whales have previously not been described.

Due to the difference in the feeding behavior and prey choice of killer and pilot whales, it was hypothesized that there could be differences in their echolocation signals. To test this, we compared the clicks recorded from the two species of sympatric toothed whales.

II. MATERIAL AND METHODS

Killer whales and long-finned pilot whales were recorded in Vestfjord, Northern Norway (67°45–68°20 N, 12°54–15°56 E) from October 25 to November 18, 2006. The recordings were made from a 100 ft. commercial whale watching boat.

A vertical linear array was deployed, consisting of four Reson TC 4034 hydrophones (sensitivity of −220 dB re 1 V/μPa, relatively calibrated to within 2 dB re 1V/μPa), with a spacing of 2 m between the first and the second hydrophone, and 1 m between the consecutive hydrophones. The hydrophones were aligned by attaching them through holes in a 4 m long PVC pole. At the end of the pole a 1 kg weight was attached to stabilize the array vertically in the water column. The hydrophones were

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connected to a conditioning box (custom-made by Niels Kristiansen, Aarhus University) containing an amplifier (30 dB) and band-pass filter (10 Hz to 200 kHz) and through an analog-to-digital converter (ADC, 16 bits, and a maximum voltage of ±5 V, 333 kHz sampling rate for the pilot whales and 500 kHz sampling rate for killer whales) to a laptop. The slight violation of the sampling theorem in the pilot whale recordings was cured by using a post-processing low-pass filter (fourth order Butterworth filter with a −3 dB cutoff frequency of 130 kHz) at a level securing that any possibly aliased components of the signals were filtered out prior to analysis. The four-channel recording program for the sound cards (NI-6251, custom-made in LabVIEW 8.2 by Alain Moriat, National Instruments, Denmark) enabled real-time monitoring of the recorded echolocation signals.

Post processing and analyses of the recordings were identical for killer whales and pilot whales. Sections containing clicks were extracted from the sound files using Adobe Audition 1.5 and were subsequently analyzed in MatLab. All clicks used for source parameter analyses were band-pass filtered (fourth order Butterworth filter, – 3 dB cut-off frequencies at 10 Hz and 130 kHz) in MatLab prior to analysis.

The signal-to-noise ratio (SNR) was measured from rms levels (within a duration of the signal containing 95% of its energy; see Madsen and Wahlberg, 2007 for details) in a frequency window of the noise being similar to the bandwidth of the signal. The SNR was larger than 20 dB in all sequences used in the subsequent analysis.

To identify on-axis clicks, defined as being recorded in a direction close to the acoustic axis of the whale, the following criteria were used:

- The signal should be detected on all four hydrophones.
- The whale had to face the array (swimming direction was estimated from consecutively localized clicks).
- The clicks needed to be of lower amplitude at the start/end of the click train compared to in the middle (the click chosen for analysis was the one of highest source level in the sequence).
- At least a 2 dB amplitude difference was required between the hydrophones, with the highest amplitude being on one of the center hydrophones.

The click intensity back-calculated to 1 m from the source was denoted the apparent source level (ASL, dB re 1 μPa at 1 m) to emphasize that the exact direction to the animal is only assumed and not measured (*sensu* Møhl *et al.*, 2000). It was assumed that the signal received on the hydrophone with the highest ASL was close to the acoustic axis of the sound beam. To further characterize the waveform of the clicks, the energy flux density (E) over time was calculated using the formula (in Urick, 1983, cf. Fig. 2 below)

$$E = \int_O^T I dt = \frac{1}{\rho c}\int_O^T p_i^2 dt = \frac{1}{f_s \rho c N}\sum_1^N p_i^2, \qquad (1)$$

where I (W/m^2) is the intensity of the signal, f_s is the sampling frequency, ρ (kg/m^3) is the acoustic density and depends on the medium, c is the speed of sound, $p(t)$ is the speed of sound, and $p(i)$ is the sampled signal. N is the number of samples in p_i and T is the duration of the signal.

Two-tailed Mann-Whitney U-tests and χ^2–tests were used for comparing source parameters (a significance level of 0.05 was used).

III. RESULTS

In total, more than 2000 clicks were recorded from killer whales. Out of these, 28 clicks met the source parameter criteria. From long-finned pilot whales 137 clicks were recorded. Twenty of these met the source parameter criteria. These close to on-axis clicks were acoustically localized at calculated distances of 20–80 m from the array for long-finned pilot whalees and 20–120 m from the array for killer whales.

A summary of the source parameters for the clicks are shown in Table I, and examples of clicks and associated spectra for both a killer whale and long-finned pilot whale click are shown in Fig. 1. Except for the rms-duration, all source parameters differed significantly between the two species (Mann-Whitney U-test, $p > 0.05$). Killer whale clicks had a longer duration (except when measured as the rms duration), a higher ASL_{pp}, and a higher energy level than pilot whale clicks. In contrast, pilot whales clicks had a broader bandwidth and higher peak and centroid frequencies. The inter-click-intervals (ICI) for killer whales were significantly shorter (7.5–12 ms) than those of pilot whales (132–137 ms). Figure 2 shows the accumulated energy as a function of time of clicks with an ASL_{pp} of 199–201 dB re 1 μPa. For the killer whales there was a plateau early in this function, while a similar plateau occurred later in the long-finned pilot whale clicks.

IV. DISCUSSION

Higher ASLs for pilot whales were to be expected due to the presumably lower target strength of the pilot whale prey items compared to the prey of the killer whales. Killer whales in Norway feed mainly on large-sized herring, with target strength of around −40 dB at 38 kHz (Peltonen and Balk, 2005). Pilot whales mainly feed on squid (Desportes and Mouritsen, 1993). Assuming that the size range of prey items is similar to the size range reported in previous measurements of target strength of various squid species, the target strength of prey items may range from −60 to −38 dB (Benoit-Bird and Au, 2001; Kawabata, 2005; Madsen *et al.*, 2007). However, pilot whales usually forage at great depths (Heide-Jørgensen *et al.*, 2002; Aguilar de Soto *et al.*, 2008) and since the recordings presented here were made in the upper water column they may not represent the echolocation signals used during foraging. This is further corroborated by the fact that buzzes with short ICIs, usually associated with foraging events in toothed whales, was not recorded from pilot whales in this study. Therefore, the pilot clicks were probably not measured during feeding events, which may explain why the source level was not as high as expected.

Simon *et al.* (2007) measured significantly lower ASLs from Norwegian killer whales than Au *et al.* (2004) measured from Canadian killer whales. Simon *et al.* (2007)

TABLE I. Source parameter data for killer whales (*Orcinus orca*) and long-finned pilot whales (*Globicephala melas*). All clicks were filtered with a 10 Hz to 130 kHz band-pass filter prior to analysis. Standard error (*SE*), range, and number of measurements (N) are indicated in parenthesis behind the mean. ASL: apparent source level; pp: peak-to-peak; rms: root-mean-square. All parameters but the RMS duration were significantly different for the two species ($p < 0.05$). The 95% duration, is the duration measured within a window containing 95% of the energy of the signal.

Source parameter	*Killer whale* *O. orca* mean (*S.E.*; **Range**; N=28)	*Pilot whale* *G. melas* mean (*S.E.*; **Range**; N=20 except when otherwise indicated)
Duration 3 dB (μs)	20 (*1.1*; **12–35**)	12 (*0.3*; **11–17**; 20)
Duration 10 dB (μs)	41 (*2.6*; **21–67**)	23 (*1.3*; **18–40**)
95% Duration (μs)	49 (*3.1*; **27–86**)	35 (*3.0*; **20–75**)
RMS duration (μs)	13 (*0.7*; **8–22**)	15 (*1.1*; **8–26**)
ASL_{pp} (dB re 1μPa pp at 1 m)	203 (*1.8*; **186–226**)	196 (*0.9*; **189–202**)
ASL_{rms} (dB re 1 μPa rms at 1 m)	193 (*1.8*; **176–217**)	185 (*1.0*; **179–190**; 18)
Energy flux density within a −10 dB duration window (dB re 1 μPa^2s at 1 m)	149 (*1.8*; **130–171**)	140 (*0.9*; **133–145**)
Energy flux density within a 95% cumulative energy window (dB re 1 Pa^2s at 1 m)	149 (*1.8*; **130–171**)	140 (*0.9*; **133–145**)
Peak frequency (kHz)	29 (*1.7*; **16–49**)	50 (*3.2*; **34–94**)
Centroid frequency (kHz)	32 (*1.5*; **21–56**)	55 (*2.1*; **37–73**)
Bandwidth −3 dB (kHz)	25 (*1.9*; **9–43**)	46 (*3.4*; **24–71**; 17)
Bandwidth −10 dB (kHz)	44 (*2.2*; **22–72**)	80 (*3.8*; **48–112**; 19)
RMS bandwidth (kHz)	12 (*0.5*; **7–20**)	20 (*0.7*; **14–25**)

hypothesized that this was caused by better hearing capabilities of the prey of Norwegian killer whales than of Canadian killer whales. The prey species of neither killer whales nor long-finned pilot whales are able to hear ultrasounds (Mann *et al.*, 2005; Szymanski *et al.*, 1999; Hawkins and Johnstone, 1978; Wilson *et al.*, 2007; Schack *et al.*, 2008). However, some of the fish species that killer whales prey upon, such as herring, can probably pick up low frequency components of the signals (Simon *et al.*, 2007). The present study contradicts the conclusion by Simon *et al.* (2007) and shows that Norwegian and Canadian killer whales emit clicks of similar intensity when recorded at similar ranges.

A comparison between the duration of the signals from the two species in the present study shows a significantly shorter duration (except for the rms-duration) and a significantly broader bandwidth for the long-finned pilot whales (Table I). A broad band signal will return echoes from a broader size range of objects than a narrow band signal and a signal with a higher frequency emphasis will result in a narrower beam, thereby reducing clutter. Whether or not the differences observed between killer whale and long-finned pilot whale clicks are large enough for such effects to become significant for the whales is still an open question.

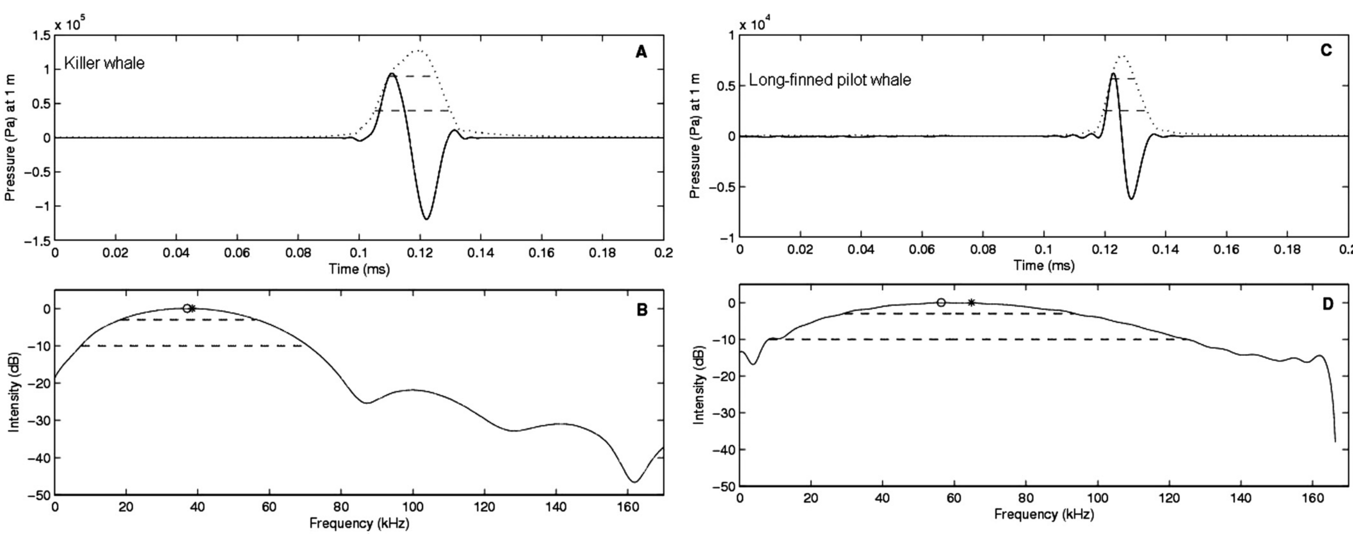

FIG. 1. Click oscillogram (solid line in A and C) and spectrum (B and D) of a killer whale (A and B) and long-finned pilot whale (C and D) click. In A and C the envelope of the signal is indicated with dotted lines and the −3 dB and −10 dB re peak levels of the envelope are shown with dashed lines. In B and D the peak frequency is indicated with a circle and the centroid frequency with a star, and the −3 dB and −10 dB re spectrum peak level are indicated with dashed lines.

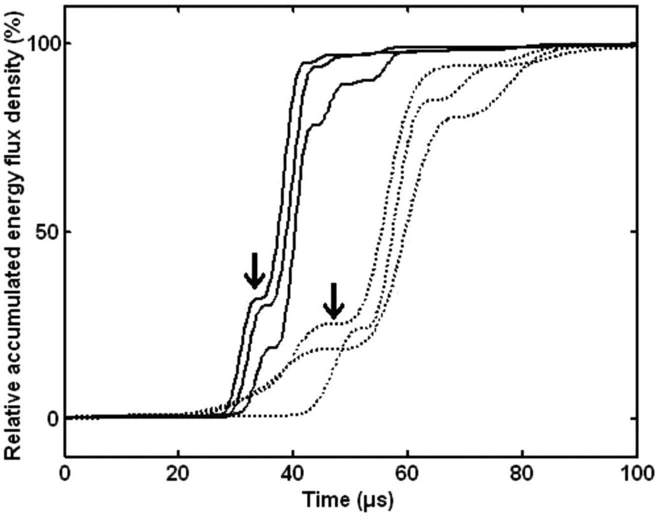

FIG. 2. Relative accumulated energy flux density as a function of time for three selected clicks with similar ASL_{pp} (200 dB re 1 μPa pp $\pm$ 1 dB) for long-finned pilot whales (solid lines) and killer whale (dotted lines).

The accumulated energy flux density increases more rapidly over time for pilot whale clicks than for killer whale clicks (Fig. 2). This is a consequence of the higher frequency emphasis and shorter duration of the pilot whale clicks. There seems to be a species-specific shape for the accumulated energy flux density increase with the plateau being reached earlier for killer whales than for pilot whales. This pattern may be useful for identifying the species that have been recorded during passive acoustic monitoring. If several species are present in the same area during recordings, the automated detection technique may ease and improve the identification of the species recorded by taking accumulated energy flux density of the species characteristic clicks into account. However, further studies to investigate how this pattern is affected by recordings on and off the acoustic axis are needed to evaluate, if this method can be used in future developments of passive acoustic monitoring of toothed whales.

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