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Beaked whales echolocate on prey

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Beaked whales (*Cetacea*: *Ziphiidea*) of the genera *Ziphius* and *Mesoplodon* are so difficult to study that they are mostly known from strandings. How these elusive toothed whales use and react to sound is of concern because they mass strand during naval sonar exercises. A new non-invasive acoustic recording tag was attached to four beaked whales (two *Mesoplodon densirostris* and two *Ziphius cavirostris*) and recorded high-frequency clicks during deep dives. The tagged whales only clicked at depths below 200 m, down to a maximum depth of 1267 m. Both species produced a large number of short, directional, ultrasonic clicks with no significant energy below 20 kHz. The tags recorded echoes from prey items; to our knowledge, a first for any animal echolocating in the wild. As far as we are aware, these echoes provide the first direct evidence on how free-ranging toothed whales use echolocation in foraging. The strength of these echoes suggests that the source level of *Mesoplodon* clicks is in the range of 200–220 dB re 1 μPa at 1 m. This paper presents conclusive data on the normal vocalizations of these beaked whale species, which may enable acoustic monitoring to mitigate exposure to sounds intense enough to harm them.

Keywords: beaked whale; *Mesoplodon*; *Ziphius*; clicks; echolocation; sonar

1. INTRODUCTION

Beaked whales are deep-diving toothed whales, and are the least known family of all marine mammals. They are one of the few groups of large mammals for which new species continue to be reported (Reyes *et al.* 1991; Dalebout *et al.* 2002). Two genera of beaked whales, *Hyperoodon* and *Berardius*, were hunted commercially and are comparatively better known. The other genera, including *Ziphius* and *Mesoplodon* are among the least known mammals. There has been growing concern that intense human-made sounds may cause mass strandings of *Ziphius* and *Mesoplodon* (Simmonds & Lopez-Jurado 1991; Frantzis 1998; Jepson *et al.* 2003). New techniques are urgently needed to study the behaviour and habitat use of these animals, and to identify risk factors for exposure of beaked whales to noise. Data on how they use sound may be particularly relevant to understanding their sensitivity to human-made sounds.

We have adapted a non-invasive acoustic recording tag (Johnson & Tyack 2003) for use with beaked whales. We report acoustic data from two deep-diving Cuvier's beaked whales (*Ziphius cavirostris*) and two Blainville's beaked whales (*Mesoplodon densirostris*) showing the production of ultrasonic clicks and echoes from prey.

2. MATERIAL AND METHODS

(a) *The tag*

The DTAG is a miniature sound and orientation recording tag. Acoustic data are sampled at 96 kHz using a 16-bit resolution sigma-delta converter. Accelerometers, magnetometers and a pressure sensor are sampled at 50 Hz to measure the orientation and depth of the tagged whale. Data are stored digitally in 3 Gb of non-volatile memory. A loss-less audio compression algorithm is used to extend the recording time. The tag is attached to the whale with a set of four small silicone suction cups using a handheld pole. The cups are vented after a programmable time to release the tag from the animal, which is recovered to download the data (Johnson & Tyack 2003).

(b) *Field site and data collection*

During September 2003 we tagged two Cuvier's beaked whales in the Ligurian Sea. The first whale, thought to be a female from a group of four adults, performed one deep foraging dive of 50 min to 824 m during a 3 h tag attachment. Data were collected on the second whale, probably an adult female from a group also including a mother, calf and a juvenile, to the full 15.6 h recording capacity of the tag. During this time, the whale made eight foraging dives to maximum depths ranging between 1000 and 1267 m. During October 2003, we tagged two Blainville's beaked whales, *Mesoplodon densirostris*, in the Canary Islands, where strandings of beaked whales simultaneous with naval manoeuvres have been reported on at least six occasions from 1985 to 2002 (Simmonds & Lopez-Jurado 1991; Martín 2002; Jepson *et al.* 2003). The first tagged *Mesoplodon*, an adult male from a group with females and calves, made six foraging dives to maximum depths ranging between 655 and 975 m in 15.4 h. The second tagged *Mesoplodon*, an adult female from a group of two adult females, made two deep dives to 730 and 815 m in 3 h.

3. RESULTS

No vocalizations were detected from the tagged beaked whales when they were within 200 m of the surface, but they all clicked almost continuously at depth. The *Ziphius* started clicking at an average depth of 475 m (range of 450–525 m) and stopped clicking when they started their ascent at an average depth of 850 m (range of 770–1150 m). The *Mesoplodon* started clicking on descent at an average depth of 400 m (range of 200–570 m) and stopped clicking when they started ascending at an average depth of 720 m (range of 500–790 m). The intervals between regular clicks for *Ziphius* were close to 0.4 s. The tagged *Mesoplodon* had a broader range of inter-click-intervals (ICI), between 0.2 and 0.4 s. Trains of regular clicks often end in a rapid increase in click rate, up to *ca.* 250 clicks s^{-1} for both species. We call this acceleration a 'buzz', in parallel with the terminology used for other odontocetes and for bats as they close in on prey (Griffin 1958; Miller *et al.* 1995).

Figure 1 illustrates the waveform and spectrum of regular clicks of *Ziphius* (figure 1*a*,*c*) and *Mesoplodon* (figure 1*b*,*d*), recorded when the tagged whale was ensonified by a conspecific. These are representative examples of clicks recorded in the far-field near the axis of the beam (see § 4). The duration of the *Ziphius* clicks is *ca.* 175 μs, whereas that of *Mesoplodon* is *ca.* 250 μs. Both the *Ziphius* and *Mesoplodon* clicks have a relatively flat spectrum from 30 kHz up to the 48 kHz Nyquist rate of our acoustic sampling. However, the *Mesoplodon* clicks have a much sharper low-frequency cut-off, reaching a −20 dB point at

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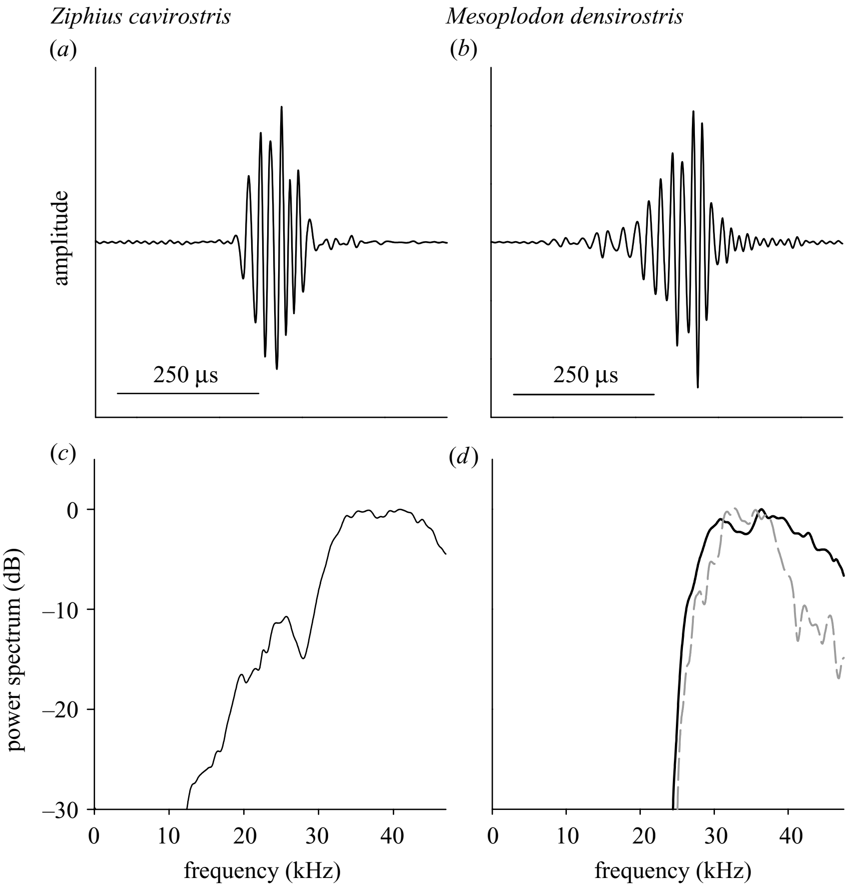

Figure 1. Waveforms and normalized spectra of far-field echolocation clicks from (*a,c*) *Ziphius cavirostris* and (*b,d*) *Mesoplodon densirostris* as recorded by the tag. A 1 kHz high pass filter was used to remove flow noise. Spectra are computed with a 256 point fast Fourier transform on Hanning windowed data. The spectrum indicated by the grey dashed line in (*d*) is the bottom echo from the click of a tagged *Mesoplodon*.

25 kHz versus 20 kHz for *Ziphius*. There may be some hint of a decrease in spectrum above 40 kHz, but our 96 kHz sampling rate was clearly insufficient to sample the full frequency range of clicks from either species. The tag received bottom echoes from clicks produced by the tagged *Mesoplodon*. The spectrum of a typical bottom echo is indicated by a dashed grey line figure 1*d*. The similarity of the echoes to our tag recordings of untagged whales nearby supports the interpretation that both signals are recordings of the forward beam of the click.

Echoes from targets in the water column are detectable in the regular clicks from all of the tagged whales, often immediately prior to buzzes. Figure 2*a* illustrates echoes recorded from a tagged *Mesoplodon* of a target on which the whale is closing. The target range closes from 12 to 3 m during the last few seconds before a buzz. Several other echoes are visible at ranges of 4–12 m at the left side of figure 2*a*, but one target predominates by −10 s before the end of the buzz. The speed at which the whale closes on the target is 1.4 m s^{-1}. It switches from regular clicking to a buzz at a range of 3 m at $x = -3.5$ s (figure 2*b*). The repetition rate is rapid enough during the buzz that one can see energy from subsequent clicks on figure 2*a* after *ca.* −3.5 s, starting at a delay corresponding to a range of 10 m. We rarely see echoes from targets during the beginning of a buzz, but strong close echoes are frequently apparent at the end of buzzes. For example, in figure 2*a* a sudden strong echo starts at *ca.* −1 s with a delay corresponding to 1 m target range, approximately equal to the distance from the rostrum to the tag.

The average number of buzzes recorded per foraging dive was 27 for *Ziphius* and 23 for *Mesoplodon*. Regular clicking resumes soon after the end of each buzz (figure 2*b*). The buzz is often associated with an increase in the dynamic acceleration of the tagged whale (figure 2*c*), suggesting a sudden movement to capture the prey. This interpretation is supported by the impact sounds at the end of 65% of buzzes recorded from *Mesoplodon*. Impact sounds were less frequently recorded from the tagged *Ziphius*, which may relate to different prey sizes or placement of the tag. While we cannot be sure that all of the echoes from targets in the water column are prey, these results suggest that at least the targets that the beaked whales close in on are prey.

4. DISCUSSION

All toothed whales investigated so far produce directional echolocation clicks (Au 1993), which must be measured in the forward beam to characterize their spectrum and level (Møhl *et al.* 2003). If this were also true for beaked whales, then the clicks recorded on the tag, located well behind the head, would be off the acoustic axis of the tagged whale. However, tags on both *Ziphius* and *Mesoplodon* also recorded click trains that we believe are from untagged conspecifics for the following reasons:

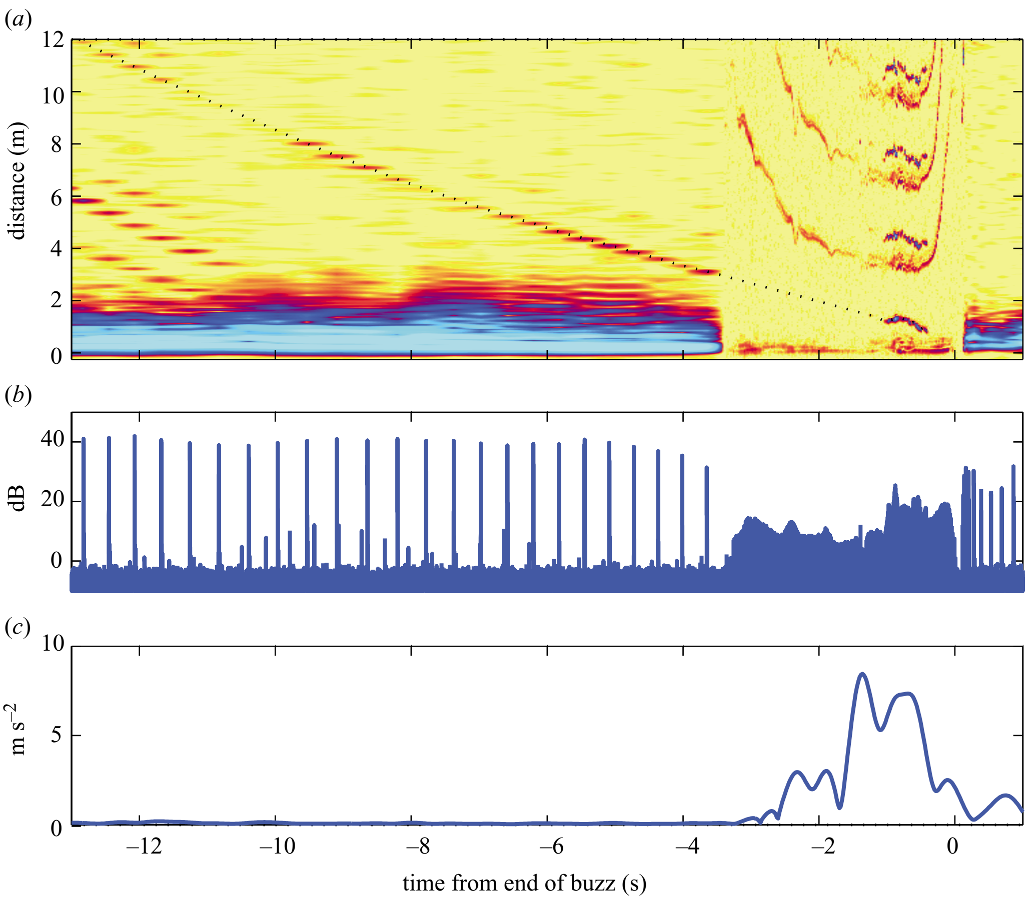

Figure 2. Echolocation of prey by a tagged *Mesoplodon densirostris*. (*a*) Alignment of successive clicks made by the tagged whale at the appropriate time on the *x*-axis. The *y*-axis indicates the time elapsed between the outgoing click and the returning echo expressed as distance to the target assuming a sound speed of 1500 m s^{-1}. The colour scale indicates the energy of the signal from blue indicating intense to yellow indicating faint. (*b*) The envelope of the recorded signal on the logarithmic scale from which (*a*) was calculated. The high-level clicks produced before −4 s are regular clicks. The clicks in the buzz from −3.4 to 0 s are so rapid that they appear continuous in (*b*). (*c*) The magnitude of the dynamic acceleration of the tagged whale. The peak at the end of the buzz probably indicates movements associated with prey capture.

(i) the tagged whales were in groups of two to six conspecifics that dived synchronously, so other whales were likely to be nearby;
(ii) these other click trains have ICIs that are similar to the clicks of the tagged whale;
(iii) the other clicks have spectra similar to echoes of clicks from the tagged whale.

We believe that the best representation of on-axis clicks in our dataset comes from clicks from untagged conspecifics recorded when they were pointing towards the tagged whale. Click trains that were not from the tagged whale typically varied from low to high to low intensity (e.g. −10 to −8 s in figure 2*b*), with the most powerful clicks having the strongest high-frequency component. This kind of pattern would be predicted if a toothed whale was scanning its sonar beam past a receiver (Au 1993). We therefore assume that by selecting clicks with the highest amplitude in a train, we are most likely to get the best representation of a click in the forward-directed beam (Møhl *et al.* 2003).

Judging from stomach contents, the prey of *Ziphius* and *Mesoplodon* is primarily squid and deepwater fishes (Mead 1989; Santos *et al.* 2001). These prey have target strengths in the −35 to −55 dB range (Lipinski *et al.* 1998; Benoit-Bird & Au 2001). If we assume 40 log-range spreading loss for the two-way travel from whale to point-source target and back, then the measured peak-to-peak echo levels are consistent with source levels in the range 200–220 dB re 1 μPa at 1 m. Owing to the limited recording bandwidth, this is probably an underestimate.

Click sounds have been previously reported for *Ziphius* (Frantzis *et al.* 2002) and *Mesoplodon densirostris* (Caldwell & Caldwell 1971), but these earlier reports differ from our results, in part because of their limited recording bandwidth. As the acoustic characteristics of beaked whale clicks become better defined, there is real potential for acoustic detection and classification of their clicks. This may be of considerable conservation value, since these whales are so difficult to sight. Acoustic monitoring may help to define beaked whale habitats and to mitigate exposure to sounds intense enough to harm beaked whales.

This study has demonstrated that *Z. cavirostris* and *M. densirostris* are highly vocal, producing high-frequency echolocation clicks above the range of human hearing. To our knowledge, this paper is the first to document echoes from prey recorded from an animal echolocating in the wild. Since the tag can also record subtle details of foraging behaviour, this leads the way to more detailed studies of how toothed whales use echolocation for foraging and orientation.

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Au, W. W. L. 1993 *The sonar of dolphins*. New York: Springer.

Benoit-Bird, K. J. & Au, W. W. L. 2001 Target strength measurements of Hawaiian mesopelagic boundary community animals. *J. Acoust. Soc. Am.* **110**, 812–819.

Caldwell, D. K. & Caldwell, M. C. 1971 Sounds produced by two rare cetaceans stranded in Florida. *Cetology* **4**, 1–6.

Dalebout, M. L., Mead, J. G., Baker, C. S., Baker, A. N. & van Helden, A. L. 2002 A new species of beaked whale *Mesoplodon perrini* sp. n. (Cetacea: Ziphiidae) discovered through phylogenetic analyses of mitochondrial DNA sequences. *Mar. Mamm. Sci.* **18**, 577–608.

Frantzis, A. 1998 Does acoustic testing strand whales? *Nature* **329**, 29.

Frantzis, A., Goold, J. C., Skarsoulis, E. K., Taroudakis, M. I. & Kandia, V. 2002 Clicks from Cuvier's beaked whales, *Ziphius cavirostris* (L). *J. Acoust. Soc. Am.* **112**, 34–37.

Griffin, D. R. 1958 *Listening in the dark: the acoustic orientation of bats and men*. New Haven, CT: Yale University Press.

Jepson, P. D. (and 17 others) 2003 Gas-bubble lesions in stranded cetaceans. *Nature* **425**, 575–576.

Johnson, M. & Tyack, P. L. 2003 A digital acoustic recording tag for measuring the response of wild marine mammals to sound. *IEEE J. Ocean. Engng* **28**, 3–12.

Lipinski, M. R., Hampton, I., Sauer, W. H. H. & Augustyn, C. J. 1998 Daily net emigration from a spawning concentration of chokka squid (*Loligo vulgaris reynaudii* d'Orbigny, 1845) in Kromme Bay, South Africa. *ICES J. Mar. Sci.* **55**, 258–270.

Martín, V. M. 2002 Summary of the report on the atypical mass stranding of beaked whales in the Canary Islands in September 2002 during naval exercises. Department of the Environment, Government of the Canary Islands. See http://www.gobcan.es/medioambiente/eng/varamientos/InformeBiologico.pdf.

Mead, J. G. 1989 Beaked whales of the genus *Mesoplodon*. In *Handbook of marine mammals*, vol. 4 (ed. S. H. Ridgway & R. Harrison), pp. 349–430. London: Academic Press.

Miller, L. A., Pristed, J., Møhl, B. & Surlykke, A. 1995 The click-sounds of narwhals (*Monodon monoceros*) in Inglefield Bay, Northwest Greenland. *Mar. Mamm. Sci.* **11**, 491–502.

Møhl, B., Wahlberg, M., Madsen, P. T., Heerfordt, A. & Lund, A. 2003 The monopulsed nature of sperm whale clicks. *J. Acoust. Soc. Am.* **114**, 1143–1154.

Reyes, J. C., Mead, J. G. & van Waerebeek, K. 1991 A new species of beaked whale *Mesoplodon peruvianus* sp. n. (Cetacea: Ziphiidae) from Peru. *Mar. Mamm. Sci.* **7**, 1–24.

Santos, M. B., Pierce, G. J., Herman, J., Lopez, A., Guerra, A., Mente, E. & Clarke, M. R. 2001 Feeding ecology of Cuvier's beaked whale (*Ziphius cavirostris*): a review with new information on the diet of this species. *J. Mar. Biol. Assoc. UK* **81**, 687–694.

Simmonds, M. P. & Lopez-Jurado, L. F. 1991 Whales and the military. *Nature* **337**, 448.