# DOES INTENSE SHIP NOISE DISRUPT FORAGING IN DEEP-DIVING CUVIER'S BEAKED WHALES (*ZIPHIUS CAVIROSTRIS*)?

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While the auditory systems of cetaceans have evolved to cope with fluctuating noise levels from natural sources, there is a growing concern that underwater noise from some anthropogenic activities may disrupt their behavior or impair their hearing (Richardson *et al*. 1995). Beaked whales may have a particular susceptibility to the harmful effects of noise as certain species strand in conjunction with naval maneuvers (Simmonds and Lopez-Jurado 1991, Frantzis 1998, Balcomb and Claridge 2001, Jepson *et al.* 2003, Martín *et al*. 2003) at least some of which have been documented to involve the use of mid-frequency sonar used to detect submarines (Evans and England 2001, Zimmer 2003). There is, however, little published information on how species of beaked whales may be affected by other anthropogenic noise sources (Malakoff 2002).

Concern about the impact of noise from motorized shipping has traditionally been focused on baleen whales, due to their use of sound at low frequencies that overlap with the main frequency band of shipping noise (Payne and Webb 1971, Richardson *et al.* 1995). Shipping is probably the main overall source of man-made noise in the marine environment (NRC 1994, 2003), and ambient noise levels at frequencies below 100 Hz in the deep ocean have increased by an estimated 15 dB since 1950 due to motorized shipping (Ross 1987, 1993; Mazzuca 2001; Andrew *et al*. 2002). While most ship noise is low frequency, Arveson and Venditis (2000) describe noise from a modern cargo ship traveling at 16 kn with third-octave source levels (SLs) over 150 dB rms re 1 μPa at 1 m at 30 kHz. Noise this high in frequency has the potential to interfere with the vocalizations of many toothed whale species. Broadband

cavitation noise is a major component of the noise from fast-moving ships and this noise source increases in level with increasing speed (Arveson and Venditis 2000). The high-frequency components of shipping noise therefore may be increasing in the oceans due to the trend in propulsion systems toward faster ships (Frisk, in Southall 2005).

This paper reports preliminary data from an onboard acoustic digital tag attached to a Cuvier's beaked whale (*Ziphius cavirostris*), showing that elevated received noise levels with ultrasonic components from a passing large ship coincided with an unusual foraging dive. With the inherent limitations of a single observation, it suggests that *Z. cavirostris* may react to intense motorized shipping noise by changing their dive and foraging behavior. Given the logistical difficulties in mounting a proper vessel-disturbance study involving beaked whales, and the paucity of data on these susceptible species, this case study provides an impetus to define a specific hypothesis about how they may respond to shipping noise and to design experiments to address this problem.

In September 2003, a Cuvier's beaked whale in the Ligurian Sea (Italy) was tagged for 15.6 h with an archival DTag (Johnson and Tyack 2003). When tagged, the whale was swimming in a group of four approximately 24 nautical miles southwest of Genoa (tagging position: 44°8′N, 8°35′E) and the tag was recovered 4 nmi farther south. The corresponding water depth in the local nautical charts was 1,400–1,500 m. DTags are miniature, suction-cup attached, sound and orientation recording tags. The tag sampled audio at 96 kHz with 16 bit resolution, while orientation and depth sensors were sampled at 50 Hz. A single-pole high-pass filter at 400 Hz was applied to the hydrophone signal to de-emphasize flow noise. An antialias filter, with a cutoff frequency of 46 kHz, was built into the sigma-delta converter. The tag was attached at 1530 local time and remained attached throughout the night. A 20-m long observation vessel tracked the whale at a distance with the aid of the radio beacon included in the tag. After release, the tag was recovered and data were downloaded for analysis in *Matlab 6.5*. The occurrence, duration, and depth of sounds from the whale and its environment were noted and quantified during the analysis.

Click and buzz sounds from the whale were recorded at the base of each of eight deep dives (Johnson *et al*. 2004). Clicking started at an average depth of 475 m (range 450–525), with long series of broadband regular clicks (RC) punctuated by short pauses and buzzes (Fig. 1). Buzzes are fast series of clicks of 2–10-s duration similar to those produced in the final phase of prey capture in other toothed whales (Johnson *et al.* 2004, Miller *et al.* 2004, Madsen *et al.* 2005) and bats (Griffin *et al.* 1960). The whale stopped clicking and started ascending at an average depth of 850 m (range 770–1150). On the basis of vocal activity, the dives could be divided into three phases: silent descent, a vocal-foraging phase, and silent ascent.

In addition to the vocal sounds, the tag recorded broadband environmental noise and noise from fluke movements and water flow over the tag during swimming. On listening to the tag recording, it was found that dive 4 coincided with elevated noise levels received from the nearby passage of a single vessel. In order to compare the noise level in this dive to that in the other seven dives, one-third-octave level (dB re. 1 μPa, rms) analysis was applied to the recording (following ANSI standard S1.6-1984).
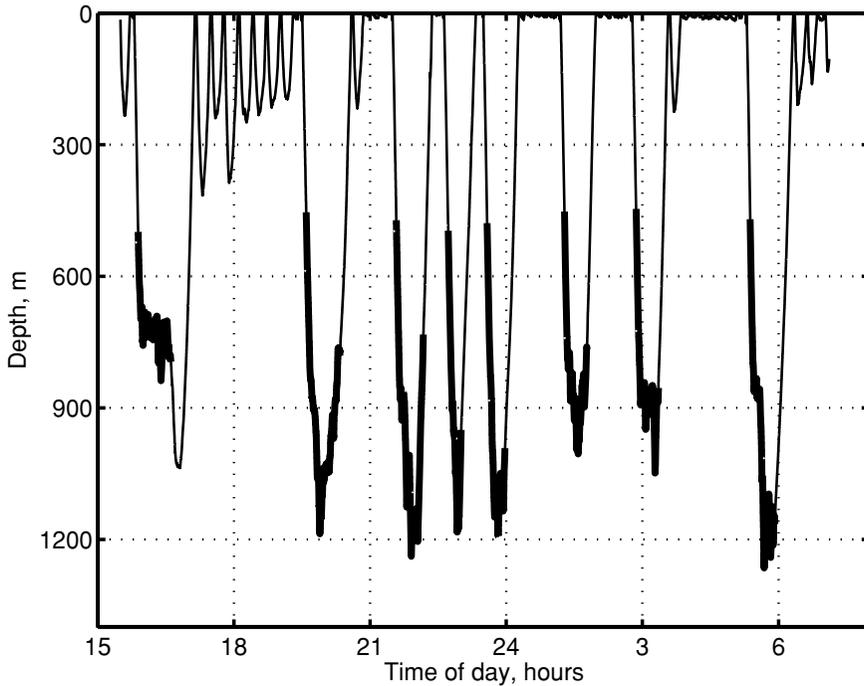
*Figure 1.* Time-depth profile of a Cuvier's beaked whale obtained from a DTag recording of 15.6 h made in September 2003 in the Gulf of Genoa, Italy. The duration of the vocal phase in each dive is indicated by the thicker line.

The low-frequency components of the signal down to 50 Hz were first emphasized to compensate for the 400 Hz high-pass filter, and the signal was then passed to a 1/3 octave filter bank. Individual filters in the bank were generated from a continuous-time prototype using the bilinear transform and a multi-rate implementation was adopted to ensure accuracy in the filter characteristics (Oppenheim *et al.* 1999).

Interference from vocalizations made by the tagged whale was avoided by performing spectral analysis only during pauses in regular clicking. Unfortunately, during the noisiest part of the ship passage in dive 4 it was sometimes impossible to distinguish pauses from buzzes due to the lower apparent level of these in the tag and the dubious pauses were therefore removed from the analysis, leading to an underestimation of the maximum noise from the boat. A total of 157 pauses were found with length greater than 5 s, averaging 0.6 pauses/min of the vocal phase. Of these, 10 were in dive 4 while 147 were in the other seven dives. Excluding the first second of each pause, which could be contaminated by echoes from a previous click (Johnson *et al.* 2004), the third-octave spectrum was computed over the following 3 s. The analysis assumes that the flow noise on the tag was essentially similar in each of the vocal phases of the dives, *i.e.*, that there are no substantial variations in the swimming speed from dive-to-dive. Assuming that the swimming speed is proportional to the fluking rate of the whale, we measured fluking from the cyclic variations that it creates in the
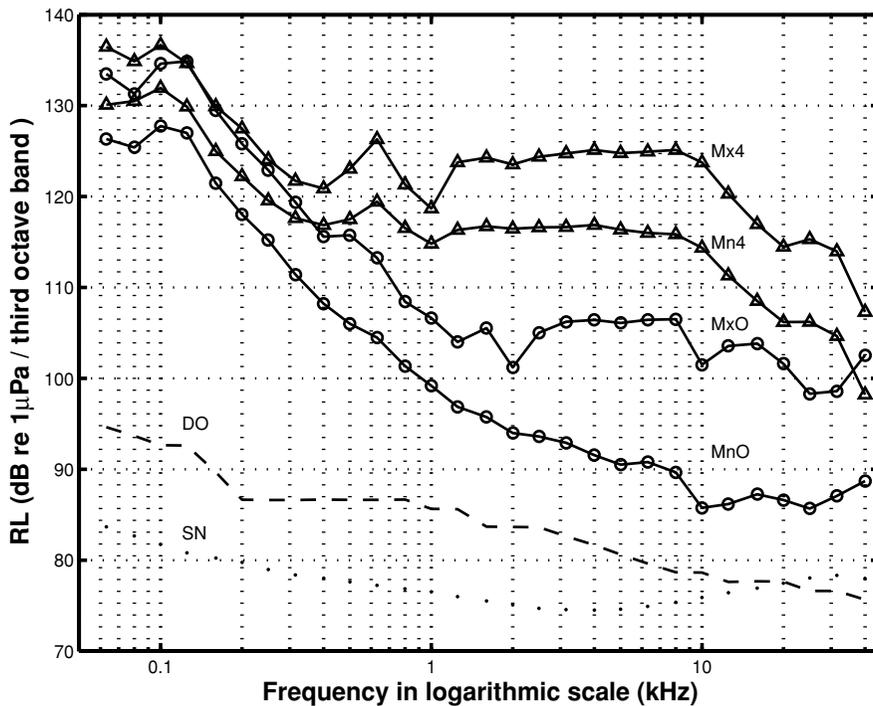
*Figure 2.*   Maximum and mean third-octave received sound levels (TOL) during the pauses of the vocal phase of dive 4 (labeled Mx4 and Mn4, respectively, upper two lines with triangles) compared to maximum and mean TOL of the pauses during the other dives (labeled MxO and MnO, respectively, two lower lines with circles). The maximum curves reflect the highest received level (RL) observed in each third-octave band in any pause of dive 4 and of the seven other dives. The dashed line (DO) represents the deep-ocean TOL at sea state 3 with heavy shipping (after Urick 1983) and the dotted line at the bottom (SN) represents the system noise of the DTag.

pitch of the whale (*sensu* Miller *et al*. 2004). The similarity of the fluking rate among dives was confirmed by comparing the rms value of the deviation of the pitch of the whale from the smoothed accelerometer data during the vocal phase of each dive. The mean value of this parameter for dive 4 was within the 95% confidence interval for the rest of the dives.

The results of the third-octave band analysis of the noise recorded in the pauses are shown in Figure 2. The two curves marked with triangles are the mean and maximum third-octave levels (TOL) for dive 4, while the two curves marked with circles are the mean and maximum TOL for the other dives. The maximum curves reflect the highest RL observed in each third-octave band in any pause of dive 4 and of the seven other dives. Below the third-octave band starting at 356 Hz, the mean TOL varies little among the dives and our aural impression is that low-frequency noise in the recording is dominated by flow noise around the tag. The flow noise measured by the tag is likely much higher than what the whale is detecting at these frequencies. At frequencies above 356 Hz, the mean TOL of dive 4 was notably elevated due to the

ship passage (Fig. 2) with the maximum received level (RL) being observed shortly after the start of the vocal phase. The ship noise was typical of a large ship (Ross 1987, Richardson *et al*. 1995) but with increased components at higher frequencies, which indicate that the ship was traveling fast enough for the propeller to cause cavitation (Arveson and Venditis 2000). The vessel passed at night so the type of ship was not recorded by the observation boat.

The maximum broadband (356 Hz–44.8 kHz) level received during the ship passage was 136 dB rms re 1 μPa, where this was computed by summing the third-octave power levels for the pause with the highest overall RL. The TOLs in this pause ranged from 107 dB rms re 1 μPa at 40 kHz to 126 dB rms re 1 μPa at 800 Hz. Given the depth of the whale at that time, the minimum distance between ship and whale was 700 m. Making the crude assumption of spherical spreading, this would indicate a broadband SL for the vessel in the frequency range 356 Hz–44.8 kHz of 193 dB rms re 1 μPa at 1 m, with individual TOLs ranging from 164 to 183 dB rms re 1 μPa at 1 m for the bands centered at 40 kHz and 800 Hz, respectively. We cannot quantify TOLs below 356 Hz due to flow noise around the tag. If the vessel passed directly over the whale at a range of 700 m, then this is likely an overestimate of the actual SL as it does not take into account reflections from the surface or seafloor (which was about 600 m below the whale at foraging depth based on charts for the region). However, if the vessel did not pass directly above the whale, *i.e.*, if the closest point of approach was >700 m, then the SL could be underestimated.

We identified two frequency bands of particular interest in comparing the noise levels between dive 4 and the other dives. The first of these covers the frequency range of *Z. cavirostris* vocalizations and would speak to the potential for the ship noise to mask echolocation of prey or reduce the ability of whales in a group to maintain contact by listening to each others' echolocation clicks. The main energy in the forward-projected *Z. cavirostris* click is concentrated near 40 kHz (Johnson *et al*. 2004) with a −10 dB bandwidth of 22 kHz, from 29 to 51 kHz (Zimmer *et al.* 2005). To cover as much of this frequency band as possible in our data we summed the power in the two highest third-octave bands, spanning from 28 to 44.8 kHz, under the assumption that masking noise is integrated over the signal bandwidth for broadband signals (Au *et al*. 2004). Although this method will underestimate the overall noise level in the click band by a few decibels due to the unmeasured noise beyond 44.8 kHz, for the following analysis we are only interested in the change in noise level with and without the vessel. The change in level in the selected third-octaves will provide a good estimate of the overall increase in noise level in the click frequency range if the ship and ambient noise spectra are smooth.

The second frequency band for comparative analysis was chosen to coincide with that of a 2.6–3.3 kHz submarine detecting sonar that has been associated with several atypical mass strandings of Cuvier's beaked whales (Evans and England 2001, Zimmer 2003). Although the relationship between mid-frequency military sonar and the strandings is not yet understood, and other sonars may play a part (for example, a 6.8–8.2-kHz sonar and a 0.45–0.7-kHz sonar were operated during some strandings, Evans and England 2001, Zimmer 2003), it is conceivable that *Z. cavirostris* may be especially sensitive to sound in this frequency band. To evaluate the contribution of the vessel noise at these frequencies we measured the power in the one third-octave
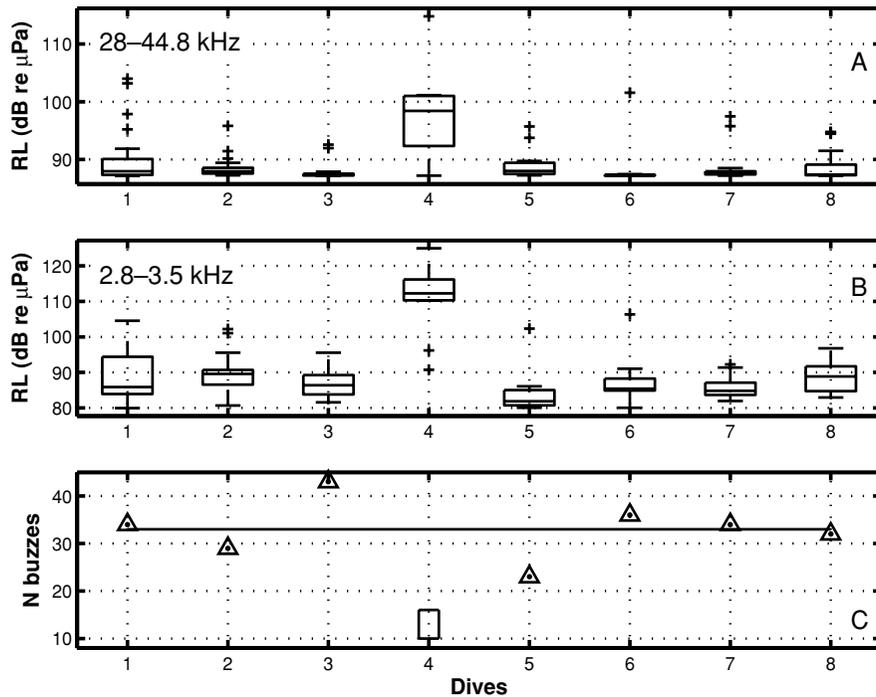
*Figure 3.* (A) and (B) Box plots of the mean noise level in each dive, as recorded by the DTag during pauses in clicking. (A) is the RL obtained by summing the power in two third-octave bands (28–44.8 kHz) covering the main energy of the forward-directed *Z. cavirostris* click. (B) RL in the third-octave band from 2.8 to 3.5 kHz, covering the frequency range of the common naval sonar used during some atypical strandings of Cuvier's beaked whale. In each panel, the crosses represent values differing by more than 1.5 SD from the mean. In both cases dive 4 shows elevated levels over the other dives. (C) Buzz count in each dive with the rectangle showing the range of values estimated for dive 4. The horizontal line represents the mean of buzz counts for dives 1–3 and 5–8.

band covering 2.8–3.5 kHz although, as can be deduced from Figure 2, any third-octave band between 2 and 8 kHz would give about the same results. For both the click and sonar analysis bands, noise levels were only computed during pauses in clicking as described above.

The mean TOL increase in the band overlapping with the sonar frequencies was 24 dB (mean RL dive 4: 117 dB rms re 1 $\mu$Pa, SD 9; mean RL other dives: 93 dB rms re 1 $\mu$Pa, SD 5) (Fig. 3). This more than 10-fold increase in noise power may have a particular impact if Cuvier's beaked whale is sensitive to mid-frequency noise. However, the higher source levels (SLs) of military sonar, a tonal and novel sound for the animals, may well provoke different responses from the whales than would broadband noise, as has been shown with right whales (Nowacek *et al*. 2003).

The mean received level in the click frequency range, computed by summing the power in the two highest third-octave bands, was 106 dB rms re 1 $\mu$Pa (SD 8) for pauses in dive 4, while it was 91 dB rms re 1 $\mu$Pa (SD 3) during pauses in the other

dives. The ship noise thus effectively increased the noise floor in the click band of *Z. cavirostris* by at least 15 dB during the vocal phase of dive 4. These figures may underestimate the actual change in RL as flow noise generated around the tag will raise the apparent ambient noise floor, and the mean RL over the full duration of the vocal phase does not reflect the maximum noise levels at the time of the closest vessel approach.

The increase of at least 15 dB in the click-band ambient noise levels will greatly reduce the maximum range of echolocation and communication if detection is noise-limited (Au 1993). For a constant signal-to-noise ratio (SNR) at the receiver, and assuming that the SL is invariant, the maximum detection range of vocalizations from another whale or of echoes from prey would be shortened according to the following simplified sonar equations (Urick 1983):

$$20 \log_{10}(R_s) + N_s = 20 \log_{10}(R_0) + N_0 \quad \text{(communicative function)}$$

$$40 \log_{10}(R_s) + N_s = 40 \log_{10}(R_0) + N_0 \quad \text{(sonar function)}$$

where $R_s$ and $N_s$ are, respectively, the detection range (m) and ambient noise (dB rms re 1 $\mu$Pa) during the ship passage, and $R_0$ and $N_0$ are the signal detection range (m) and ambient noise (dB rms re 1 $\mu$Pa) in the other dives. Under this simple model, with $N_s - N_0 = 15$ dB, the maximum sonar detection range is reduced to 42% of its normal value, *i.e.*, a range reduction factor (after Møhl 1981) of 2.4. The maximum communication range is reduced to 18% of its normal value, a range reduction factor of 5.6. Consequently, if the whale auditory system is noise-limited, the mean ship-induced elevation in the ambient noise during dive 4 will reduce the maximum range of echolocation by more than half, and the maximum range at which it can detect sounds from conspecific whales will be reduced by more than five times.

The buzz sounds made periodically during foraging are considered to represent the terminal phase of closing on prey in bats (Griffin *et al*. 1960), sperm whales (Gordon 1987, Miller *et al*. 2004), and beaked whales (Johnson *et al*. 2004, Madsen *et al*. 2005). The number of buzzes in a dive may then offer an indication of the foraging efficiency of the whale (Miller *et al*. 2004), given that the cost of transport from the surface to foraging depths and back is approximately constant for each dive. The tagged *Z. cavirostris* performed eight foraging dives to similar depths (mean 1,144 m; min. 1,005 m; max. 1,265 m; SD 99), but dive 4 had a duration of 42 min, *i.e.*, 15 min shorter than the mean of the other dives (57 min, SD 12 min). The difference was due to a considerable shorter vocal phase (17 min), with a duration of just 41% of the total dive length in comparison to the 60% (SD 7.6) dedicated on average to echolocation in the other dives (34 min, SD 7.8 min). The vocal phase duration in the seven unaffected dives fit a normal distribution although not unambiguously so (Kolmogorov-Smirnov test with the Lilliefors modification). Nonetheless, if the normal approximation is valid, the probability ($P$) of a dive having a vocal phase of the same duration or less than that in dive 4 is significantly low ($P = 0.02$). If instead the data are fit to a log-normal distribution a similar result holds ($P = 0.002$).

Buzzes are usually clearly audible in the DTag recording despite their relatively low apparent level as compared to regular clicks (Madsen *et al.* 2005). However, during the noisiest part of the ship passage in dive 4, the elevated noise level made it impossible to distinguish buzzes from pauses on some occasions and so it is only possible to give a range of values for the buzz count in this dive, namely from 10 to 16. The minimum value corresponds to the number of buzzes detected aurally, while the maximum includes also the pauses during regular clicking when the elevated ship noise made it impossible to be sure whether there was a buzz or not. If the higher buzz count is used, the buzz rate (buzzes/min) in dive 4 is similar to that in the other dives (mean 1/min; SD 0.2). However, given the short vocal phase of dive 4, even the maximum buzz count in this dive (16) was significantly lower than for the other dives. Again this was tested by fitting a normal distribution (mean 33, SD 6) to the buzz count in the seven control dives (an ambiguous fit under the same goodness of fit test) and then computing the probability of the buzz count being 16 or less given the normal distribution. The result, $P = 0.004$, indicates that the number of prey-capture attempts was markedly lower in dive 4 as is also evident in the box-plots of Figure 3, although it is acknowledged again that the likelihood of this event cannot be reliably construed from such a small sample. If the buzz counts are fit to a log-normal distribution, dive 4 remains a significant outlier ($P = 0.0002$). There were no significant differences between dive 4 and the other dives in terms of maximum depth, vertical speed in descent or ascent, or in the time lag between the start of the dive and the start of the vocal phase, implying that the transport costs were roughly equal across dives. If we estimate foraging efficiency as the buzz count divided by the total dive time, the curtailed vocal phase in dive 4 translates into a reduction in foraging efficiency of more than 50% for this dive as compared to the other dives. Although no general conclusion can be drawn from this isolated example, we suggest three possible ways that the elevated ship noise in dive 4 might impact the whale: (1) by reduction in echolocation range due to masking of prey echoes, (2) behavioral disruption by elevated noise levels in one or several frequency bands, or (3) by masking acoustic signals used to coordinate the group behavior of Cuvier's beaked whales diving together.

The results presented here came from a *Z. cavirostris* tagged some 25 km south of the busy ports of Savona and Genoa. Dense vessel traffic in the area includes ferries (conventional and high speed), tankers, cargo ships, and recreational boats. While beaked whales in the area may well be habituated to moderate noise levels from ship traffic, the apparent response to a close ship approach reported here suggests that they may not habituate to the elevated noise levels from such a close approach, which may be less common.

This paper reports data from a small set of foraging dives, one of which has a markedly shorter vocal phase and therefore a lower foraging efficiency. This disrupted foraging dive coincides with a noisy vessel passage. We demonstrate that ship noise can lead to elevated ambient noise levels at high frequencies with the potential of masking toothed whale echolocation and communication. It is therefore clear that noise from motorized shipping has a potential impact on a much wider range of cetacean species than just baleen whales which communicate at the low frequencies typically associated

with shipping noise (Payne and Webb 1971). Masking has been identified as the primary auditory effect of vessel noise on marine animals (Southall 2005). With respect to the observed reduction in foraging in a *Z. cavirostris* dive coincident with the noisy passage of a large vessel, it is clear that our single observation is circumstantial and no firm conclusions can be drawn in terms of a causal relationship. However, we believe that the lack of behavioral data on Cuvier's beaked whale together with its well-known sensitivity to man-made sound, make this single result noteworthy. Given the trend of the shipping industry toward using increasingly fast vessels which produce more noise in the frequency ranges at which beaked whales are sensitive, and at frequencies at which they communicate and echolocate for food, it will be important to design studies to evaluate whether this case reflects a general problem with implications for beaked whale conservation.

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