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Exposure to seismic survey alters blue whale acoustic communication

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The ability to perceive biologically important sounds is critical to marine mammals, and acoustic disturbance through human-generated noise can interfere with their natural functions. Sounds from seismic surveys are intense and have peak frequency bands overlapping those used by baleen whales, but evidence of interference with baleen whale acoustic communication is sparse. Here we investigated whether blue whales (*Balaenoptera musculus*) changed their vocal behaviour during a seismic survey that deployed a low-medium power technology (sparker). We found that blue whales called consistently more on seismic exploration days than on non-exploration days as well as during periods within a seismic survey day when the sparker was operating. This increase was observed for the discrete, audible calls that are emitted during social encounters and feeding. This response presumably represents a compensatory behaviour to the elevated ambient noise from seismic survey operations.

Keywords: seismic survey; acoustic communication; ambient noise; whale calls; compensation

1. INTRODUCTION

The dramatic elevation in human-generated ocean noise over the last century has raised concern about the impact on cetaceans, which rely on acoustic signalling for communication, orientation, locating prey and predators. (Richardson *et al.* 1995; NRC 2005). The sounds from marine exploration surveys are one of several anthropogenic noise sources that have been identified as eliciting behavioural reactions in marine mammals (reviewed in Gordon *et al.* 2004). Seismic surveys rely on systems that produce impulsive, high intensity sounds (190–250 dB re 1 μ Pa, peak to peak), with most energy below 200 Hz (Richardson *et al.* 1995). The peak frequencies of these sounds overlap the acoustic signals and estimated hearing ranges of baleen whales (Wartzok & Ketten 1999). Such acoustic interference could reduce a whale's ability to detect biologically relevant signals. Despite this concern, and the increase in oil and gas prospecting surveys into deeper waters, there is sparse knowledge on the acoustic responses of baleen whales to sounds from seismic exploration.

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In this study, we investigated the calling behaviour of blue whales (*Balaenoptera musculus*) relative to seismic operations that occurred in the St Lawrence Estuary (SLE), Canada, an important marine mammal feeding ground (Bellefleur *et al.* 2006). The seismic reflection method deployed was a sparker, a low-medium power technology (2–8 kJ EG&G sparker: source level = 193 dB re 1 μ Pa, peak to peak, frequency band = 30–450 Hz; peak energy = 60–250 Hz) (Bellefleur *et al.* 2006). Blue whale calls are frequency-modulated audible sounds emitted during short-range social interactions and feeding (Berchok *et al.* 2006; Oleson *et al.* 2007). They are discrete, short (1–4 s) and transient, with a frequency band of 30–200 Hz and might therefore be susceptible to interference from trains of seismic survey pulses (figure 1). We investigated whether call rates changed during periods with, relative to periods without, sparker operations.

2. MATERIAL AND METHODS

Data were collected in the SLE (49.5' N, –69.0' E), where seismic sparker explorations were conducted within an 11-day period (1–11 August 2004; electronic supplementary material, figure S1). Because we had no information on the schedule and tracks of the survey transects, the position and movement of the seismic vessel relative to the whales could not be determined. Information on the acoustic behaviour of blue whales was therefore gathered from the coincidence of sparker noise events as detected on our acoustic recordings.

Sounds were recorded using an array of five bottom-mounted Marine Acoustic Recording Units (MARU; depth = 60–100 m, sampling rate = 1 kHz) (Cornell Bioacoustics Research Program). Whale abundance and individual identifications were obtained during daily boat-based surveys in the MARU area. On 4 days, sparker pulses were clearly recorded on all units, and thus were most certainly audible for whales in the MARU area (electronic supplementary material, table S1). Sound data from these 4 days and from 4 days without sparker activity were broken into 10 min samples, and the number of calls determined for each sample. All 10 min samples were divided into those with and without seismic pulses. To account for the possible influence of social context on calling activity, only samples for which we had concurrent visual observations and counts for the number of blue whales were used in the analysis.

To test for independence of the 10 min samples, we performed a Wald–Wolfowitz runs test for each day. The independent 10 min samples were used to compare call production between the 4 days with and the 4 days without seismic survey noise. Throughout a day, during which sparker pulses were detected, there were periods with and without sparker activity. Within these days, we compared call rates for the periods with and without sparker pulses. To evaluate whether the onset of seismic testing influenced whale vocal behaviour, we compared the number of calls within 1 h blocks with sparker pulses to the immediately preceding 1 h blocks without pulses.

3. RESULTS

During the 11 survey days, we sighted 17 individuals (plus five unidentified). Six of them were re-sighted on multiple (3 or less) days. The mean number of individuals observed during 'seismic' days was four, and three during 'no-seismic' days. Of all calls noted, 77 per cent were audible on at least three recorders and therefore within or close to the MARUs.

In total, sparker pulses were detected on 49 h (12 ± 3 h d^{-1} , $n = 4$). We obtained 117 10 min samples from the days with and 129 from the days without sparker pulses. Out of these 117 samples, 51 contained sparker pulses and 66 did not. The results from the Wald–Wolfowitz runs tests revealed that the samples were independent (electronic supplementary material, table S2).

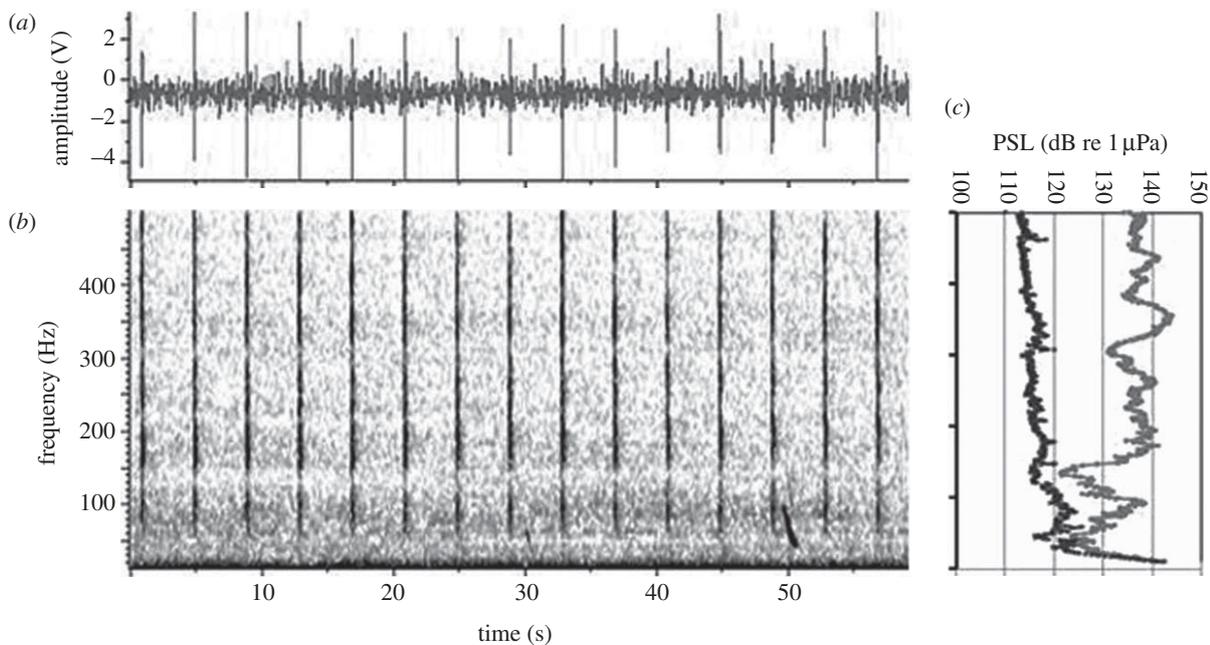


Figure 1. (a) Waveform, (b) spectrogram (fast Fourier transform = 1024, 50% overlap) showing sparker pulses (vertical lines) and a blue whale call and (c) power spectral density levels (PSL) (0–500 Hz) for a no-seismic acoustic sample (black line) and a seismic acoustic sample taken from an adjacent time segment (grey line).

Blue whales emitted significantly more calls on seismic than on no-seismic days as shown by the results of the generalized linear model (GLM) with quasi-Poisson error structure ($n = 246$, $\chi^2 = 30.94$, $p = 0.0003$) (figure 2a), and the response was independent of the number of individuals observed ($n = 246$, $\chi^2 = 2.28$, $p = 0.32$). Within the 4 days with sparker pulses, blue whales generally called more during periods with, than during periods without, sparker pulses (GLM: $n = 117$, $\chi^2 = 35.42$, $p = 0.0003$). The number of blue whales had no effect (GLM: $n = 117$, $\chi^2 = 3.21$, $p = 0.27$) (figure 2b). The onset of the sparker activity affected call production, as revealed by a significant increase in call number in seismic 1 h blocks following 1 h no-seismic blocks (paired Wilcoxon signed-rank test: $n = 7$, $Z = -2.207$, $p = 0.031$) (figure 2c).

4. DISCUSSION

Blue whales responded to noise from seismic sparker operations by increasing call production. Acoustic reactions of cetaceans to airgun activity include reduced vocalization rates (e.g. Goold 1996), no vocal changes (e.g. Madsen *et al.* 2002) or cessation of singing (e.g. McDonald *et al.* 1995). This study provides, to our knowledge, the first evidence for an increase in vocal behaviour in response to seismic exploration noise in cetaceans. This type of vocal adjustment has only been reported in response to continuous noise from vessels (Buckstaff 2004; Doyle *et al.* 2008) but never to a multiple pulse noise (Southall *et al.* 2007). By increasing its rate of calling, the animal increases the probability that its signal will be successfully received by conspecifics. This is consistent with the prediction from information theory, which states that an increase in call production compensates for the masking of information by noise (Shannon &

Weaver 1949). Ship noise may also have affected calling activity. However, the study site is crossed by a busy shipping lane and vessel noise was regularly present. We therefore exclude that it accounted for the changes in acoustic behaviour reported here.

Other short-term vocal adjustments observed across taxa exposed to elevated ambient noise levels include shifting call frequency, increasing call amplitude or duration and ceasing to call (reviewed in Brumm & Slabbekoorn 2005; Nowacek *et al.* 2007). In baleen whales, North Atlantic right whales (*Eubalaena glacialis*) exposed to high shipping noise increase call frequency (Parks *et al.* 2007), while some humpback whales (*Megaptera novaeangliae*) respond to low-frequency active sonar playbacks by increasing song length (Miller *et al.* 2000). Our data do not allow reliable measurements of source amplitude because of the inability to precisely determine the sender's position. Owing to the high natural variability in call duration and frequency modulation (Berchok *et al.* 2006; L. Di Iorio 2006, unpublished data), changes in these parameters cannot be unequivocally attributed to elevated noise level.

Behavioural responses to noise exposure are generally highly variable and context dependent (Wartzok *et al.* 2004). Travelling blue and fin whales (*Balaenoptera physalus*) exposed to seismic noise from airguns have been reported to stop emitting redundant songs (McDonald *et al.* 1995; Clark & Gagnon 2006). By contrast, we found increased production of the transient, non-redundant calls during seismic sparker operations. This suggests that blue whales respond to noise interference according to the context and the signal produced. For animals engaged in near-term, proximate communication, there is probably an advantage in acoustic behaviours that maintain the immediate social link, while for animals engaged in long-term singing directed to a distant audience,

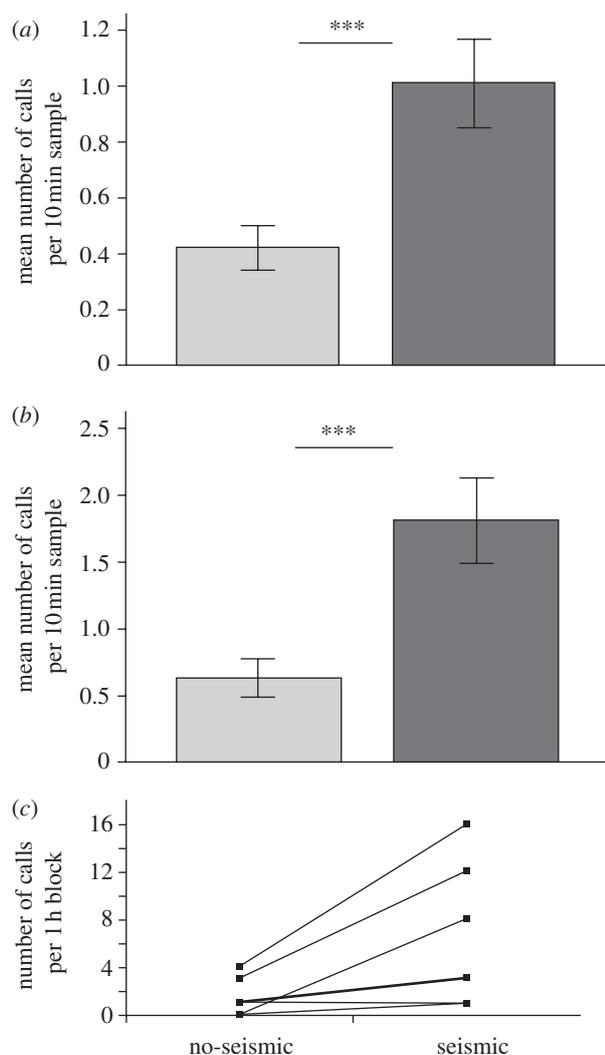


Figure 2. Comparison of blue whale call production on (a) days with and without seismic operations and (b) during periods within those seismic operation days when sparker pulses were and were not detected; ***GLM (quasi-Poisson), $p < 0.001$. (c) Calling activity during adjacent 1 h no-seismic and 1 h seismic blocks. Bold line indicates two occurrences with the same vocal change.

information loss is minor if singing is temporarily interrupted. Although we could not test this hypothesis owing to the lack of individual compensatory responses, and because SLE blue whales were not singing in early August (L. Di Iorio 2006, unpublished data), this study offers valuable cues for further investigations.

Our results clearly show that blue whales change their calling behaviour in response to a low-medium power technology that is presumed to have minor environmental impact (Duchesne *et al.* 2007). In fact, the mean sound pressure impinging on the MARU area, and thus probably on the whales present there, was relatively low, 131 dB re 1 μ Pa (peak to peak) (30–500 Hz) with a mean sound exposure level of 114 dB re 1 μ Pa² s (90% energy approach for duration estimate; cf. Madsen 2005). The relevance of the observed vocal adjustment to an individual whale's well-being is unknown. However, the SLE is an important feeding area where blue whales acquire energy and also a place where this wide-roaming,

highly dispersed population congregates to engage in social interactions (Sears 2008). Reducing an individual's ability to detect socially relevant signals could therefore affect biologically important processes. This study suggests careful reconsideration of the potential behavioural impacts of even low source level seismic survey sounds on large whales. This is particularly relevant when the species is at high risk of extinction as is the blue whale (IUCN 2008).

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