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North Atlantic right whales (*Eubalaena glacialis*) ignore ships but respond to alerting stimuli

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North Atlantic right whales were extensively hunted during the whaling era and have not recovered. One of the primary factors inhibiting their recovery is anthropogenic mortality caused by ship strikes. To assess risk factors involved in ship strikes, we used a multi-sensor acoustic recording tag to measure the responses of whales to passing ships and experimentally tested their responses to controlled sound exposures, which included recordings of ship noise, the social sounds of conspecifics and a signal designed to alert the whales. The whales reacted strongly to the alert signal, they reacted mildly to the social sounds of conspecifics, but they showed no such responses to the sounds of approaching vessels as well as actual vessels. Whales responded to the alert by swimming strongly to the surface, a response likely to increase rather than decrease the risk of collision.

Keywords: *Eubalaena glacialis*; ship-strike; controlled exposure experiment

1. INTRODUCTION

North Atlantic right whales (*Eubalaena glacialis*) were hunted for centuries (Reeves & Mitchell 1986), but despite protection from whaling since 1935 the population has not recovered and is in decline and at risk of extinction (Caswell *et al.* 1999; Clapham *et al.* 1999). Although other populations of right whales appear to be recovering from whaling (Best *et al.* 2001), a combination of factors is probably contributing to the failure of *E. glacialis* to recover. The North Atlantic species, for example, has a thinner blubber layer than their southern relatives (Miller *et al.* 2001; Moore *et al.* 2001), which may indicate some level of nutritional stress. Anthropogenic mortality in the form of ship strikes and entanglement in fishing gear, however, is directly and significantly hampering their recovery. Ship strikes are the largest single contributor to these deaths, and account for *ca.* 35% of all known mortalities (Knowlton & Kraus 2001; Laist *et al.* 2001). Right whales continue to die from vessel collisions, even though they can theoretically hear approaching ships (Richardson *et al.* 1995; Ketten 1998), and mitigation strategies have been developed to locate whales, to notify ships of whale locations, and even to redirect vessel traffic.

The question of why whales do not move out of the path of oncoming ships has been debated by biologists (Terhune & Verboom 1999; Laist *et al.* 2001). Some anecdotal observations suggest that right whales only respond when vessels approach to within a very close range. Right whales off the eastern coast of North America are frequently exposed to vessels, and they may have habituated to the sounds of approaching vessels at greater distances (Richardson *et al.* 1995; Terhune & Verboom 1999; Laist *et al.* 2001). Another problem is that the vessel noise received by whales at or near the surface may be complicated and/or attenuated due to the effects of the physical properties of the ocean on sound propagation, thus providing limited or confusing cues to the whales. Specifically, the propagation path from the source of vessel noise, primarily the propeller, to the whale's ear can be complicated. Variation in the temperature, salinity and pressure of sea water causes sound to refract. As a sound wave passes up or down through horizontal layers of sea water with different properties, it will tend to refract vertically. In the case of a whale at the surface in a deep water environment (more than 200 m) where sound at the surface is refracted downwards, a direct propagation path is unlikely, and the noise from the propeller will most likely be severely attenuated in the horizontal direction (Urick 1983). Sound energy from vessels can, however, propagate into surface waters in shallow water environments (less than 200 m) owing to interactions with the bottom, although this propagation depends on the type and depth of sediment present (Urick 1983). Although right whales inhabit primarily shallow water environments (Kraus *et al.* 1986), the overall effects of these phenomena on vessel noise propagation, and therefore the amount of acoustic energy reaching a whale, are difficult to predict and are best investigated experimentally (Urick 1983; Kinsler *et al.* 2000). Additionally, ships produce unique sound radiation patterns (Richardson *et al.* 1995), which further complicate the sound field. So, the lack of response to approaching ships by whales near the surface could be due to a variety of physical factors that compromise the cues a whale might otherwise use to detect and localize an oncoming ship.

Behavioural observations in the Bay of Fundy have documented the typical foraging dive patterns of right whales. These results indicate that individual whales in this summer foraging area display stereotyped dive patterns, with the depth and duration of dive varying by individual and presumably the depth of the food source (Murison & Gaskin 1989; Nowacek *et al.* 2001). During their summer feeding activity in the Bay of Fundy, these whales are also exposed to significant vessel traffic ranging from small fishing boats to oil super-tankers. The Bay of Fundy in the summer is then an ideal situation for this work because the behavioural patterns of the whales are

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well known and the vessel traffic is comparable to that in the rest of their range (Russell *et al.* 2001). We studied collision risk factors and the efficacy of different mitigation strategies by conducting controlled sound exposures with whales tagged with a multi-sensor acoustic recording tag.

2. METHODS

We tested the responses of whales in the Bay of Fundy summer foraging area to four stimuli: vessel noise as the test stimulus, right whale social sounds and an alert signal as alternative stimuli, and silence as an experimental control. We used an archival digital acoustic recording tag (DTAG) to record the acoustic and motor behaviour of the whales in the presence of these exposures. This tag has been non-invasively deployed on several species of marine mammal including right whales (Nowacek *et al.* 2001; Johnson & Tyack 2003). In addition to recording all sounds at a sampling rate of 32 kHz, a Nyquist rate of 16 kHz, well above the best known vocal and hearing ranges of the whales (Clark 1982; Ketten 1998), the DTAG simultaneously records the pitch, roll, heading and depth of the whale and temperature of the water at a sampling rate of 46 Hz (Johnson & Tyack 2003). After tagging a whale, we waited until it returned to normal behaviour, which, based on our earlier results, required two dive cycles. We then positioned the playback boat at the location where the whale dived. After 2 min, the approximate time required for the whales to reach foraging depths (Nowacek *et al.* 2001), we began the sound exposure with a Lubell underwater speaker (LL9162) in 2002 or J-13 underwater sound transducer (Naval Undersea Warfare Center) in 2001 suspended from the boat moving slowly along the whale's last known heading. The maximum source level (SL) of the playback was 173 dB re 1 μPa at 1 m, and no whale received the same stimulus twice nor more than three total exposures as stipulated by our research permit. We monitored the behaviour of the tagged whales throughout the experiments from the flying bridge of a 24 m research vessel.

For the silent stimulus, the amplifier and speaker were operated as normal, but with no input signal (figure 1*a*). The right whale social sound stimulus used recordings of socially active groups of right whales (Parks 2003). These vocalizations tend to last for 1–5 s and occur in the 500–4000 Hz frequency range (figure 1*b*). The vessel noise stimulus was recorded from a 120 m container ship as it passed within 100 m of a recording station. This was a 20 min continuous signal with most energy from 50 to 500 Hz (figure 1*c*), and the amplitude rose and fell to mimic an approaching and passing vessel. The alert sound was an 18 min exposure consisting of three 2 min signals played sequentially three times over. The three signals had a 60% duty cycle and consisted of: (i) alternating 1 s pure tones at 500 and 850 Hz; (ii) a 2 s logarithmic down-sweep from 4500 to 500 Hz; and (iii) a pair of low-high (1500 and 2000 Hz) sine wave tones amplitude modulated at 120 Hz and each 1 s long (figure 1*d*). The alert signals were designed with three specific goals: (i) to pique the mammalian auditory system with disharmonic signals spanning the whale's estimated hearing range (Edworthy & Meredith 1994; Ketten 1998); (ii) to maximize signal to noise ratio, i.e. use signals that would be distinct from the background and resist masking; and (iii) to provide localization cues for the whales. Finally, we measured the response of tagged whales to transiting vessels (i.e. research and whale watching vessels excluded) that passed within 1 nautical mile of the whale.

3. RESULTS

The swimming/diving response of whales exposed to the alert signal differed markedly from the hundreds of stereotyped dives recorded during current and previous experiments (Nowacek *et al.* 2001). The stereotypy of the normal dives extends to several aspects of an individual whale's behaviour including the angles and rates of ascent and descent, the fluke stroke rate (measured from the pitch record (Johnson & Tyack 2003)), and the amount of time spent in each part of the dive cycle. No significant deviations from these diving patterns occurred in the five whales exposed to the silent stimulus, the seven whales exposed to whale vocalizations or the five whales exposed to the vessel approach stimulus (table 1). Parks (2003) has documented strong approach responses of some whales to the playback of right whale social sounds, but while none of the tagged whales in this study showed significant diving responses, several did change heading to temporarily orient towards the source. Five out of six whales exposed to the alert signal, however, significantly altered their regular behaviour and did so in identical fashion. Each of these five whales: (i) abandoned their current foraging dive prematurely as evidenced by curtailing their 'bottom time'; (ii) executed a shallow-angled, high power (i.e. significantly increased fluke stroke rate) ascent; (iii) remained at or near the surface for the duration of the exposure, an abnormally long surface interval; and (iv) spent significantly more time at subsurface depths (1–10 m) compared with normal surfacing periods when whales normally stay within 1 m of the surface (see table 1 and figure 1 for all of these responses). The sixth animal ('Eg3103') showed no detectable response to the alert signal (table 1).

The strong response to the alert signal was an important experimental control demonstrating that the experimental design was capable of eliciting a strong response with an appropriate stimulus. The reaction observed in the five responding whales appears to be a response to the signal itself and not simply due to a variation in the received level (RL) of sound. There was no statistical difference in the maximum received levels, measured at the whale and analysed by octave bands, of the alert compared with the vessel noise exposures ($t = 2.01$, d.f. $= 5$, $p < 0.1$). The absence of a response to the vessel playback matches our observations of five opportunistic approaches of tagged whales. These whales were approached to within less than 1 nautical mile by passing vessels (table 1), and their lack of response suggests that whales are unlikely to respond to the sounds of oncoming vessels even when they can hear them.

4. DISCUSSION

Even though five out of the six whales exposed to the alert stimulus responded strongly, the response has several features that lead us to question whether the alert would be effective as a ship strike mitigation measure. By swimming to and remaining near the surface, instead of staying at depth, the whales most probably increased their risk of being struck. Under ideal conditions (e.g. favourable sighting weather and skilled lookouts), forcing the whales to the surface might assist collision mitigation, but by stay-

Table 1. Maximum RLs, ascent fluke stroke rates, surface intervals and subsurface time for tagged right whales under experimental conditions.
(Several of the tagged whales have been identified and matched to the catalogue (Hamilton & Martin 1999), and their 'Eg' number is given. Unidentified whales were given 'names', which consist of the two-digit year followed by the Julian day on which it was tagged (number) and the letters distinguish animals tagged on a given day. 'No playback' refers to dives taken when no stimulus was presented, and values shown for this category are means with the number of dives shown in parentheses after the fluke rate. For each whale, the max RL is in dB re 1 μPa and is the highest received sound level in the band of the exposure during the experiment, fluke stroke rates are in hertz and were measured as a whale swam to the surface during exposure, surfacing intervals (i.e. time spent at less than 10 m depth between dives) are in seconds, and subsurface times (i.e. time spent at 1–10 m depth during a surfacing interval) are in seconds. Ascent fluke rate and surface intervals during exposures were compared with the set of no playback results using a Student's *t*-test, and subsurface time as a portion of the total surface interval for each condition was tested using χ^2. A single asterisk indicates values significantly different from the no playback case at $p < 0.05$, and double asterisks indicate values significant at $p < 0.01$. In the 'vessel' column, results reported in bold indicate data collected during opportunistic vessel approaches. These data were collected only for approaches by transiting (i.e. research and whale watch excluded) motor vessels where the vessel passed within 1 nautical mile of the whale. Data for two whales '02_213g' and '02_232d' included two such approaches, and both are reported in the vessel column. While these approaches occurred at different points in the dive cycle, we have reported data for the same variables as in the playbacks.)

whale		no playback	alert	silent	whale sounds	vessel
02_213b	max RL					
	fluke rate	0.1435 (7)				
	surface interval	125				
	subsurface time					
02_213g	max RL		148	134	148	**135 | 142**
	fluke rate	0.1848 (15)	0.2259**	0.1843	0.1835	**0.1950 | 0.1788**
	surface interval	189	762**	203	177	**189 | 191**
	subsurface time	22	522**	13	11	**15 | 18**
02_220f	max RL		143			
	fluke rate	0.1925 (4)	0.2296*			
	surface interval	244	666**			
	subsurface time	0	474**			
Eg2350	max RL		137			
	fluke rate	0.1776 (15)	0.2041**			
	surface interval	314	442*			
	subsurface time	37	236**			
Eg3109	max RL		135	118		133
	fluke rate	0.1260 (21)	0.4139**	0.1833		0.0993
	surface interval	124	401**	72.5		128
	subsurface time	12	288**	10		15
02_232d	max RL		133	124		**136 | 132**
	fluke rate	0.1479 (14)	0.2064**	0.1608		**0.1342 | 0.1389**
	surface interval	222	896.9**	170		**211 | 225**
	subsurface time	41	610**	21		**38 | 45**
02_233a	max RL					**136**
	fluke rate	0.1771 (5)				**0.1593**
	surface interval	228.5				**214**
	subsurface time	54				**48**
Eg3103	max RL		134	120	148	129
	fluke rate	0.2126 (8)	0.2181	0.2066	0.2064	0.2299
	surface interval	140.6	163	124	222	149
	subsurface time	2.6	0	0	3	0
Eg2145	max RL				136	133
	fluke rate	0.1724 (15)			0.1861	0.1715
	surface interval	178			180	172
	subsurface time	12			8	5
Eg1142	max RL					139
	fluke rate	0.1726 (5)				0.1738
	surface interval	214				198
	subsurface time	6				4

ing just below the surface, the whales were vulnerable but seldom visible. Although some whales did swim on a heading that moved them out of the path of the playback boat, our experiment was not a good test of the 'horizontal' avoidance response because the playback vessel moved much more slowly than a ship under normal operation. Any future work evaluating the potential benefit of any such horizontal avoidance must be weighed against the cost of the increased time at the surface. Also, avoidance should be studied as a function of vessel speed for any evaluation of risk factors for collision. Additionally, even if the whales attempted to move out of the path of the

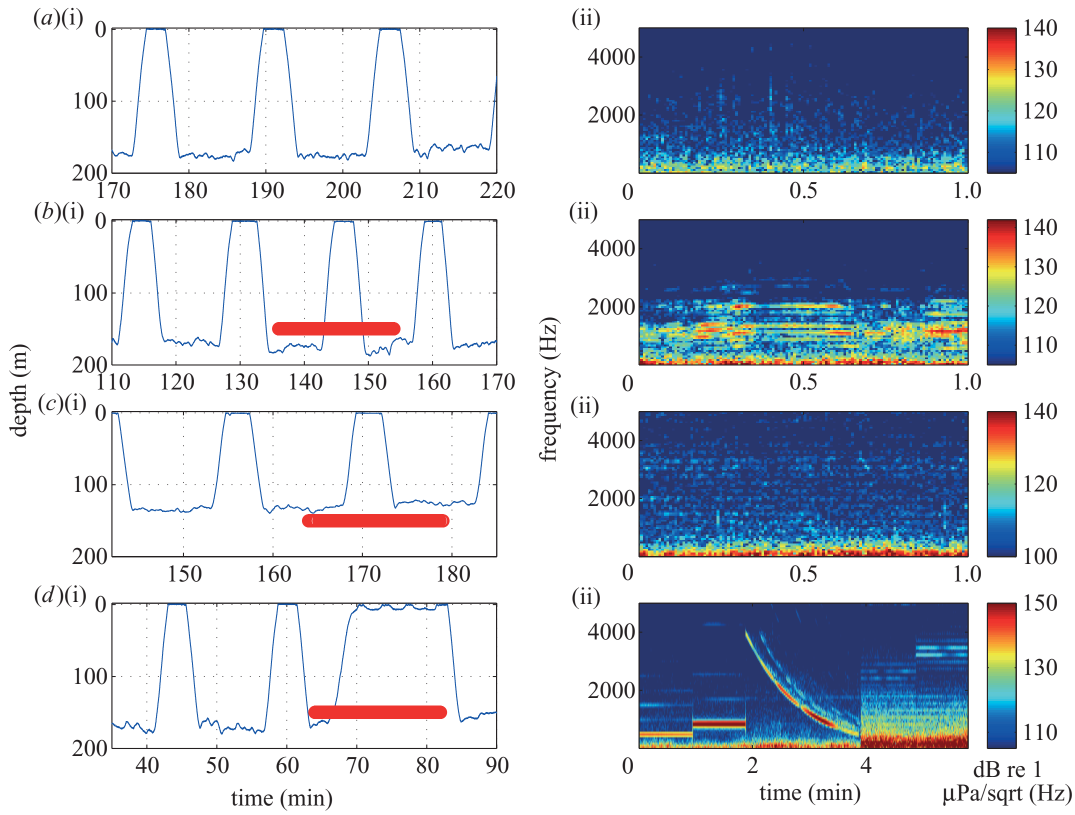

Figure 1. Swimming/diving behaviour and received sounds during control and sound exposure dives. (*a–d*)(i) show a time–depth profile for dives before, during and after exposures, and (*a–d*)(ii) show a representative spectrogram (time versus frequency) and RL of the sounds recorded on the tag: (*a*)(ii) no playback RL = 130 dB; (*b*)(ii) whale RL = 148 dB; (*c*)(ii) vessel RL = 140 dB; and (*d*)(ii) alarm RL = 148 dB. The times on the dive profiles are in minutes since the tag was attached to the whale. Red bars indicate the period of exposure to each stimulus. (*a*) Silent control; (*b*) whale social sound; (*c*) vessel noise exposure; and (*d*) the alert signal. Note the change in dive profile in response to the alert signal, including the time spent near, but not at, the surface during the exposure. The spectrogram in (*d*) shows an edited sequence of the alert signals so that each signal could be displayed. The first recording on the tag of each of the three types of alert signal is shown, although each signal occurred several times before the next type started (see text for description of signal order and duration). The increased noise for the last signal, after minute 4 in the spectrogram, resulted from increased flow noise over the tag caused by the whale's increased swim speed as it swam to the surface.

playback boat, right whales spend much of their time in areas of heavy vessel traffic (Kraus *et al.* 1986; Russell *et al.* 2001), so there is often more than one ship to which to respond. Finally, the sixth whale exposed to the alert signal showed no detectable response. In this case the alert signal would not decrease or increase the risk of collision relative to an encounter without the alert. All of these factors suggest that alerting stimuli would only be appropriate for mitigation after extensive study of the horizontal avoidance response as a function of vessel speed, and could only be one component of a comprehensive strategy to reduce the risk of collision.

Not only are there unresolved questions regarding the effect of the alert stimulus on the risk of a collision, but the behaviour of the responding whales has negative energetic consequences. The whales both lose foraging time and expend excess energy during their high-powered ascent and subsurface swimming. The actual metabolic cost of the rapid ascent is difficult to calculate. The power requirements for streamlined swimming vertebrates are proportional to the cube of the velocity (Webb 1975), and the whales' dramatically increased fluke stroke rates (table 1) suggest a strong and sustained increase in swimming speed. This manoeuvre could cost these whales significant energy, especially if repeated often. The energetic cost is especially alarming considering the reduced blubber thickness in this population (Miller *et al.* 2001). Any underwater sounds with an acoustic structure similar to our alert stimulus may also disrupt normal behaviour and evoke costly responses. This research suggests that signals like our alert are likely to disrupt feeding behaviour at received levels of only 133–148 dB re 1 µPa for the duration of the sound exposure, with return to normal behaviour within minutes of when the source is turned off.

None of the whales exposed to either approaches by transiting vessels or to our playbacks of ship noise displayed any of the responses seen to the alert stimulus (table 1). They did not respond even when we know they could hear the signals because the RLs of the playbacks as well as the opportunistic approaches were at least as strong as and contained frequencies similar to those that stimulated a strong response to the alert signal. Therefore, we must conclude that it is the alert signal itself, and not differences in RL between the different stimuli, that elicits the response. This lack of response to vessel noise at *ca.* 135 dB re 1 µPa could be very dangerous. For example, a vessel with an SL of 185 dB re 1 µPa would produce 135 dB re 1 µPa at ranges of only *ca.* 300 m based on simple spherical spreading, and, depending on the actual sound propagation, the level at this range would probably be less than 135 dB (Urick 1983). A large commercial vessel 300 m from a whale that is travelling at typical ocean speed of *ca*. 20 knots would pose a significant threat to the whale as it would travel this distance in *ca*. 30 s. Anecdotal observations of responses at less than 100 m are consistent with response at some higher exposure range, which perhaps could be the subject of future work.

A possible explanation for the difference in response to the alert versus vessel noise stimuli is that whales have habituated more to vessel noise, which is continuous and ubiquitous, than to the alert, which is intermittent and had not been introduced before these experiments. Habituation to the alert signal was not directly tested, although the one whale that showed no response was the last animal tested and was known to have been in the general area for four of the five other exposures before it was the experimental subject. Future efforts to stop collisions between ships and right whales will need to take into account the whales' lack of response to the sounds of oncoming vessels. The only obvious solution remains the difficult one of separating the vessels from the whales and/or slowing vessels to a safe speed to improve the possibility of detecting whales and/or reduce blunt trauma injuries, which are responsible for many whale mortalities (Knowlton & Kraus 2001).

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