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A behavioural dose-response model for migrating humpback whales and seismic air gun noise

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A B S T R A C T

The behavioural responses of migrating humpback whales to an air gun, a small clustered seismic array and a commercial array were used to develop a dose-response model, accounting for the presence of the vessel, array towpath relative to the migration and social and environmental parameters. Whale groups were more likely to show an avoidance response (increasing their distance from the source) when the received sound exposure level was over 130 dB re 1 μPa^2·s *and* they were within 4 km of the source. The 50% probability of response occurred where received levels were 150–155 dB re 1 μPa^2·s *and* they were within 2.5 km of the source. A small number of whales moving rapidly close to the source vessel did not exhibit an avoidance response at the highest received levels (160–170 dB re 1 μPa^2·s) meaning it was not possible to estimate the maximum response threshold.

1. Introduction

The development of mitigation measures to reduce the impact of anthropogenic sound on marine mammals involves a number of analytical tools, one of which is the dose-response model. This model, in theory, relates an animal's probability of responding to some measure of the received sound 'dose' from the sound source, in the expectation that a higher a 'dose' should increase the chance of the animal responding. Typically, a sigmoidal curve is used for the relationship, which includes the threshold response level (minimum received level to elicit a response), the level with a response probability of 0.5 (RL_{p50}) and the level at which 100% of the animals respond (response probability of 1.0). These values can then be used to set exposure limits for mitigation purposes. For example, the U.S. Navy currently uses an empirical dose-response probability-curve developed by Finneran and Jenkins (2012) to assess the likely behavioural impact of naval sonar on some cetacean species. For this particular model, the threshold response level was set at 120 dB re 1 μPa, the RL_{p50} level at 165 dB re 1 μPa, and a response probability of 1.0 at 200 dB re 1 μPa (levels in dB re 1 μPa here are mean square, also known as root mean square). Other studies, specifically testing the response of various cetacean species to naval sonar, found the RL_{p50} level to be 150 dB re 1 μPa (Blainville's beaked whale *Mesoplodon densirostris*; Moretti et al., 2014), 170 dB re 1 μPa (long-finned pilot whales *Globicephala melas*; Antunes et al., 2014), 124 to 144 dB re 1 μPa (a captive harbor porpoise *Phocoena phocoena*; Kastelein et al., 2013), 162–174 dB re 1 μPa (captive bottlenose dolphins *Tursiops truncatus*; Houser et al., 2013b), and 147 to 158 dB re 1 μPa (captive California sea lions *Zalophus californianus*; Houser et al., 2013a), illustrating a large inter-species range of response levels to one sound source; sonar. Rather than separate responses by species, a more recent study combined the responses of three different species (killer whale *Orcinus orca*, sperm whale *Physeter microcephalus* and long-finned pilot whale *Globicephala melas*) to naval sonar but generated different dose-response curves according to response 'severity' (Harris et al., 2015). For low and medium response severities, the RL_{p50} levels were 153 and 155 dB re 1 μPa^2·s (Sound Exposure Level: SEL) respectively, and the 1.0 probabilities were 167 and 180 dB re 1 μPa^2·s respectively. For the highest response severity, the curve asymptoted at a 0.1 probability at 160 dB re 1 μPa^2·s. Another study of the severity of response of humpback whales (*Megaptera novaeangliae*), minke whales (*Balaenoptera acutorostrata*) and bottlenose whales (*Hyperoodon ampullatus*) to naval sonar found an RL_{p50} of 179–185 dB re 1 μPa^2·s (cumulative SEL). This severity was considered to have the potential to affect vital rates in humpback whales (Sivle et al., 2015).

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Fewer studies, however, have used seismic air guns as the sound source. Studies of feeding and migrating gray whales (*Eschrichtius robustus*) exposed to a 100 cubic inch air gun source found the RL_{p50} level for feeding whales to stop feeding was 173 dB re 1 μPa (Malme et al., 1986). For migrating gray whales to avoid the source, the RL_{p50} was 170 dB re 1 μPa (Malme et al., 1984). However, humpback whales (*Megaptera novaeangliae*) showed no evidence of avoidance at exposure levels up to 172 dB re 1 μPa (Malme et al., 1985) suggesting inter-species differences. Other studies of gray, bowhead (*Balaena mysticetus*), and humpback whales have shown that seismic air gun sounds with received levels of 160–170 dB re 1 μPa caused obvious avoidance behaviour in a "substantial portion" of exposed groups (Richardson et al., 1995). Therefore, not only are there inter-species differences, but results differ between studies on the same species. Currently, the threshold for "behavioural disruption from impulsive sounds" used by National Marine Fisheries Service is 160 dB re 1 μ Pa (National Marine Fisheries Service, 2016).

The response of an animal to a stimulus can be categorised physiological and/or behavioural. When considering the response of marine mammals to a sound source, high received levels can lead to changes in hearing, such as a temporary shift in their hearing threshold (which can become an injury with a permanent threshold shift at higher levels; e.g. Finneran, 2015). Physiological changes can be related to the stress response, which may be driven by increases in hormone levels such as noradrenaline, adrenaline (e.g. Romano et al., 2004) and cortisol (e.g. Hunt et al., 2014). This hormonal response results in changes to various body systems, such as the cardiorespiratory (e.g. Lyamin et al., 2016) and immune system (e.g. Romano et al., 2004). If the stimulus is perceived as immediately threatening, the animal can exhibit 'escape' or 'defensive' behaviours known as the "fight-or-flight" response (originally defined in Cannon, 1915). Animals may also use a passive coping strategy known as "freezing" behaviour (first described by Engel and Schmale, 1972). If the stimulus is of no immediate threat, the animal may use an avoidance strategy such as horizontal avoidance, cryptic behaviours (e.g. camouflage), or grouping together. Applying this to the humpback whale for example, in response to an immediately threatening situation (when attacked by a killer whale), this species either exhibits either 'flight' (Ford and Reeves, 2008) or 'mobbing' behaviour (Pitman et al., 2017). In response to a situation where there is no immediate threat, such as the presence of more distant potential predator, they cease feeding, change dive patterns to become more cryptic, and exhibit directional horizontal avoidance such as alternating 90 degree turns in female-calf pairs (Curé et al., 2015).

The National Oceanographic and Atmospheric Administration, based in the United States, carry out work under the U.S.'s Marine Mammal Protection Act (MMPA). The MMPA prohibits the "take of marine mammals—including harassment, hunting, capturing, collecting, or killing—in U.S. waters and by U.S. citizens on the high seas". Under this act, permanent changes in hearing (i.e. Permanent Threshold Shift: PTS) are regarded as Level A takes (injury) and temporary changes in hearing (Temporary Threshold Shift: TTS) as well as behavioural changes are regarded as Level B takes. Level B behavioural takes are considered less severe than Level B physiological takes (TTS), but are likely to occur at lower received levels compared to hearing effects. Partly due to the difficulties of measuring any physiological response in large, wild, marine mammals, most studies on the effects of anthropogenic noise on large baleen whales have concentrated on measuring a behavioural response only. Examples of these behavioural responses in whales include changes in dive behaviour, swimming speed, and/or two-dimensional movement patterns (Antunes et al., 2014; Dunlop et al., 2015, 2016, 2016, 2017, 2017; Gailey et al., 2007; Malme et al., 1983, 1984; McCauley et al., 2003; Richardson et al., 1985, 1986; Robertson et al., 2013), an avoidance reaction as determined by expert group consensus (Miller et al., 2014) and/or changes in breathing patterns (Dunlop et al., 2017). However, separating a significant behavioural response to the sound source from a response to some other factor (for example, the vessel towing the source), or from the natural variation in an animal's behaviour, can be difficult as this requires some sort of response threshold that accounts for this large behavioural variation. Various techniques, including qualitative scoring (Miller et al., 2014), 'change-point' analysis (e.g. Antunes et al., 2014; DeRuiter et al., 2013; Miller et al., 2014), simulations (Antunes et al., 2014), 'reaction scores' (Curé et al., 2012), 'severity scores' (Williams et al., 2014), and comparing the magnitude of horizontal avoidance to baseline behaviour (Dunlop et al., 2016) have been used to decide 'cut-offs' between what could be considered a 'response' and 'no response'. However, a large sample size, as well as robust *baseline* and *control* datasets, are necessary to capture the within-population variance in normal behaviour and separate this from likely reactions caused by the sound stimulus.

This large variance in observed reactions is likely to be due to many factors, such as the probable perception of the stimulus (for example, threatening versus non-threatening as mentioned above), the combination of received level and source proximity (e.g. DeRuiter et al., 2013; Dunlop et al., 2017) and individual factors such as age (e.g. Houser et al., 2013b), sex (e.g. Symons et al., 2014), behavioural state (e.g. Sivle et al., 2012; Goldbogen et al., 2013) and social context (e.g. Ellison et al., 2011; Dunlop et al., 2013, 2015, 2017). The behavioural responses of large whales to seismic air guns, for example, range from no detectable response (Broker et al., 2015; Malme et al., 1984, 1985; Yazvenko et al., 2007a) or small changes in behaviour (Dunlop et al., 2015, 2016, 2017; Gailey et al., 2007; Malme et al., 1983, 1984; McCauley et al., 2003; Richardson et al., 1985, 1986; Robertson et al., 2013) through to possible displacement of animals from an area (e.g. Castellote et al., 2012; Muir et al., 2016; Yazvenko et al., 2007b). Taken together, there is no consistent response threshold level within these studies. For example, within humpback whales, McCauley et al. (2003) found that resting female-calf pairs showed avoidance responses at relatively low received levels (129 dB re 1 $\mu Pa^2 \cdot s$) whereas, in general, migrating humpback whales showed clear course changes in response to the air gun at received levels of 144–151 dB re 1 $\mu Pa^2 \cdot s$. By contrast, Malme et al. (1985) did not find any consistent avoidance of feeding humpback whales to air guns at received levels of 172 dB re 1 μPa, though, on a small number of occasions, a startle response at air gun onset was noted at 150–169 dB re 1 μPa at ranges of up to 3 km from source. It is this large variability in their response, even for the same species to the same stimulus, which makes assessing and mitigating the behavioural impacts of underwater noise on marine mammals difficult.

The BRAHSS (Behavioural Response of Australian Humpback whales to Seismic Surveys) study aimed to quantify the behavioural response of migrating humpback whales to various seismic array sources. Part of this study developed a measure of behavioural avoidance (Dunlop et al., 2016), and used this metric in an initial dose-response model. This model related the magnitude of an avoidance response to the distance and received level of the noise source, whilst accounting for potential responses to the source vessel (Dunlop et al., 2017). Results for exposure to a single 20 cubic inch air gun and a small array of 440 cubic inches found a proportion of humpback whale groups changed their travelling behaviour to increase their distance from the source when exposed to air gun signals (considered to be an avoidance reaction if over a certain threshold determined from the normal movements in the absence of a source). This avoidance response was of a greater magnitude if the received level was both above 140 dB re 1 $\mu Pa^2 \cdot s$ and the group was also within 3 km of the source (Dunlop et al., 2017). The study presented here extends the analysis methodology developed by Dunlop et al. (2017) to include a full commercial seismic air gun array. Because of the experimental design and large amount of data collected, we could assess the effects of array size (comparing the responses between a single 20 cubic inch (0.33 l) air gun, a small 4-stage 140 cubic inch array (2.29 l) and a full 3130 cubic inch (51.29 l) commercial array), towpath relative to the group (across the migration compared to against the migration), and other social and environmental