Marine mammals and the impacts of anthropogenic noise: Considerations for the design of large acoustic behavioural response studies such as BRAHSS

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ABSTRACT

Sound travels with greater efficiency in water than does light, which is quickly absorbed and scattered. As a consequence, a wide variety of marine taxa use sound for communication, foraging and generally sensing their environment. Since the 1970s there has been increasing concern about the potential impacts of underwater anthropogenic noise on marine animals. Sources range from short-term coastal ones such as pile driving, to those which contribute long-term, sustained increases in ambient noise, such as shipping. Cetaceans (whales, dolphins and porpoises) are a group of marine animals thought to be at particular risk to impacts from anthropogenic noise. One type of study that has been used to determine the short-term impacts of noise on various taxa is the Behavioural Response Study (BRS) where animals are exposed to a noise and their behavioural responses are measured. While BRS are relatively straightforward for captive animals, most species of cetaceans are not kept in captivity and experiments with adequate levels of control are difficult. One such study, however, is the Behavioural Response of Australian Humpback whales to Seismic Surveys (BRAHSS), which commenced in 2010. Migrating humpback whales were exposed to high level, impulsive sounds from arrays of seismic airguns off the Sunshine Coast, north of Brisbane, and off Dongara in Western Australia. The airguns, from a single 20 in^3 airgun to an array of 3130 in^3, were towed behind a source vessel while whales were tracked and their behaviours observed from small boats and land stations. The success of the project required the accurate estimation of the received levels of the source vessel noise and airgun noise, as well as careful measurement and interpretation of behavioural data. This large study is an example of the need for careful study design and collaboration between experts in several fields including underwater acoustics and animal behaviour.

1. INTRODUCTION

Marine mammals are a relatively disparate group of animals that include approximately 130 species of whales and dolphins (the cetaceans), seals and sea lions (the pinnipeds) and, manatees and the dugong (the sirenians) as well as polar bears and sea otters. They are found in a great variety of marine (and in some cases, estuarine and riverine) habitats, with species found in all oceans, from the topics to the poles. They inhabit coastal, shelf and pelagic environments, many species living almost entirely within shallow waters while some exploit the rich resources of the mesopelagic, diving regularly to depths of 2km or more (e.g. sperm whales, beaked whales, elephant seals) (Hindell et al. 1992; Schorr et al. 2014). While some groups are entirely aquatic (cetaceans and sirenians), others are amphibious to various degrees, with part of their life cycles on land (or ice) and others in the water (pinnipeds, polar bears and otters).

Sound travels with greater efficiency in water compared to light as light is quickly absorbed and scattered while sound travels with very little absorption, particularly at low frequencies (Richardson et al. 1995). As a consequence, marine mammals have evolved to utilise sound actively and passively in all biologically important behaviours (Tyack 2009). These include the use of passive acoustics for sensing the environment, detection of predators, and probably navigation; the use of active acoustics (echolocation) for foraging; and both active and passive acoustics for finding other individuals of the same species, attracting and assessing mates, and other forms of social communication such as maintaining contact between females and calves (Richardson et al. 1995).

Although the sounds of marine mammals had been studied to some extent previously, it was not until the 1970s the noise generated by human activities in the oceans became a significant concern in terms of it having an impact on these animals. Payne and Webb (1971) were among the first to highlight the issue, pointing out that low frequency noise from shipping may have effectively reduced the communication range of some recently described baleen whale sounds from 280 km to 90 km, reducing the potential area of communication by up to 90%. They noted at the time that this reduction in communication range may be particularly important in light of the drastic population reductions suffered by many species of baleen whales at that point, reducing population density and probably increasing the reliance on long distance sound to find mates.

Over the last 40 years, the pace of progress in terms of regulation and research has been variable. Various regulatory frameworks, such as the US Marine Mammal Protection Act and the Australian Environmental Protection and Biodiversity Conservation Act, accept that noise poses a threat and there is a strong desire in many countries to develop effective regulations. Examples include the development of guidelines for underwater acoustic exposure limits (Southall et al. 2007; National Marine Fisheries Service 2016), the EU Marine Strategy Framework Directive (MSFD: 2008/56/EC) which includes measuring ambient and high source level anthropogenic noise throughout its waters, and regulatory frameworks for specific activities such as seismic surveys by the oil and gas industry (e.g. Department of Environment, Water, Heritage and the Arts 2008; Department of Conservation 2015).

The pace of research to support these regulatory frameworks, however, has been variable. While considerable work has been undertaken in some areas such as developing audiograms (see Erbe et al. 2016 for review) and measuring hearing thresholds affected by noise (see National Marine Fisheries Service 2016 for review), these have primarily been in species that are held in captivity. In the open ocean, research on hearing sensitivities, with and without the effects of noise, is much more difficult. Also, while it is relatively straight forward to measure underwater noise, it is difficult to conduct experimental, or even good observational, work on the impacts of noise on behaviour of free-ranging marine mammals and much of the early literature on disturbance is based on anecdotal observations (Richardson et al. 1995). Ship time for work at sea is expensive and the environment can be harsh and dangerous. The animals themselves, depending on species, can be cryptic; often difficult to find, accessible for behavioural observation only fleetingly while at the surface between dives, and usually very difficult to tell one individual from another. While the development of some tags, particularly the DTAG at the Woods Hole Oceanographic Institution (Johnson & Tyack 2003), has helped enormously in terms of measuring noise at the animals and underwater behaviour, they are difficult to deploy and do not help with issues of expense, finding cryptic animals or harsh environmental conditions.

2. POTENTIAL IMPACTS AND SOURCES OF ANTHROPOGENIC NOISE

Anthropogenic noise could theoretically impact marine mammals in a variety of ways and at a variety of distances from the noise source (Figure 1). Relatively far from the source, noise could potentially affect marine mammals as soon as it is audible. Dunlop et al. (2013) showed that migrating humpback whales (*Megaptera novaeangliae*) responded to exposure to short tones at signal-to-noise ratios close to the theoretical critical ratio of mammalian hearing suggesting that they were responding close to the threshold of detectability. Beluga whales (*Delphinapterus leucas*) responded to icebreakers tens of kilometres away that were likely to be near the limits of acoustic detection (Finley et al. 1990). Generally, however, behavioural reactions are likely to occur well above threshold. Behavioural reactions include displacement from the area around the source which may have biologically significant impacts if the area includes crucial habitat, e.g. foraging areas, as well as changes in vocal behaviour (Miller et al. 2000, 2009; DeRuiter et al. 2013; Goldbogen et al. 2013; Nowacek et al. 2015; Blackwell et al. 2015).

Masking is another impact that may occur some distance from the source (reviewed in Erbe et al. 2016). This is where the anthropogenic noise effectively increases the background noise thus reducing the range over which animals can effectively detect other sounds. This can have obvious impacts in terms of finding mates and other aspects of social communication as well as predator detection and perhaps navigation. This may be particularly important for distant animals where only small increases in ambient noise due to relatively low levels of anthropogenic noise may be enough to cause masking (e.g. Erbe & Farmer 1998, 2000).

Closer to the source, additional impacts may relate to impairment of hearing. Noise may be loud enough to cause either a temporary threshold shift in hearing (TTS) or, at higher levels, a permanent threshold shift (PTS). This hearing impairment will have potentially severe consequences for the individual due to impairment of important functions that rely on passive and active acoustics (National Research Council 2005). Until recently, the levels at which PTS and TTS might occur in marine mammals was unknown, but experiments over the last 15 years or so on a relatively small number of individuals over a small number of species (reviewed in Finneran 2015) has enabled the production of tentative guidelines for acoustic exposure to impulsive and continuous sounds. The first such guidelines, Southall et al. (2007) represented an important stage in putting boundaries on acceptable exposure levels for marine mammals. These guidelines are currently being reviewed and, in a parallel process, the US government has also recently produced detailed guidelines on exposure levels that may cause threshold shifts (National Marine Fisheries Service 2016). While this is a start, there is still a long way to go in terms of gathering more data in more species to improve these guidelines (Wright 2015). Recent studies have also shown that a warning sound played to captive false killer whales (*Pseudorca crassidens*), bottlenose dolphins (*Tursiops truncatus*) and belugas can reduce the sensitivity of hearing by up to 15dB and may serve to protect hearing in certain circumstances (Nachtigall & Supin 2013, 2014; Nachtigall et al. 2016). The mechanism for this change in sensitivity is not currently known.

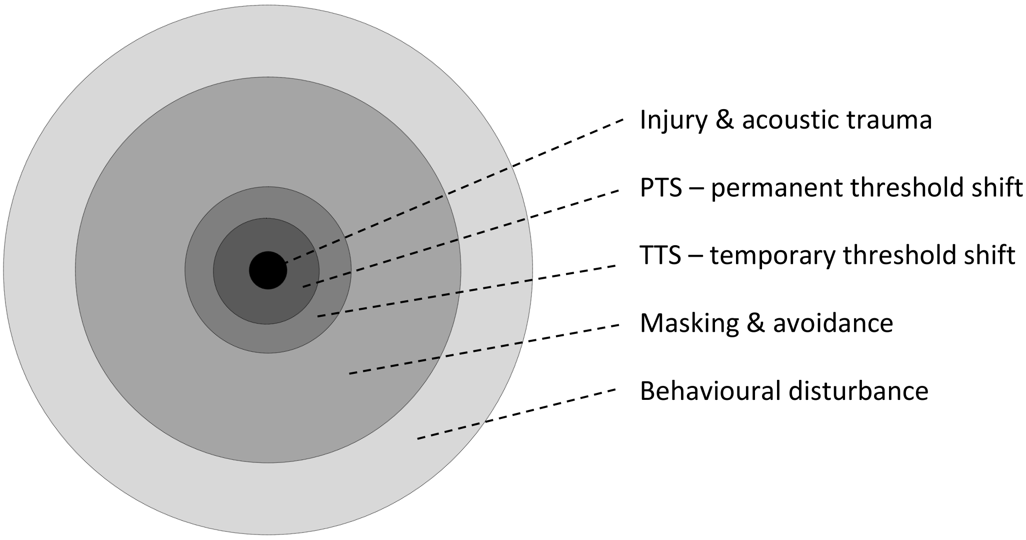

Figure 1: Progression of potential impacts of noise as a function of distance from a source (after National Research Council 2005). Distances will vary depending on several factors including the intensity of the source, the band of the acoustic energy, the hearing range of nearby animals, and the propagation conditions and transmission loss of acoustic energy with distance.

One of the most fundamental data sets required for estimating how noise may impact on animals at all levels is basic information on what the animals can hear, preferably in the form of an audiogram that reveals absolute and relative sensitivity across the full range of hearing for that species. Again, while progress has been made and there are audiograms available for some species data (e.g. Pacini & Nachtigall 2016), for many groups there are no data. Notably there are still no direct measurements of hearing for any species of baleen whale. While we assume that they hear well over the frequencies of their own vocalisations (supported by anatomical evidence, e.g. Ketten 2000), the only baleen whale audiogram currently available is an indirectly derived, finite element model using a fin whale calf skull (Cranford & Krysl 2015). The lack of direct audiogram data is due largely to there being no baleen whales available for experimental work in captivity as well as issues relating to conducting electrophysiological work on such large animals.

Typical sources of underwater noise include shipping, naval sonar, seismic surveys, oil and gas extraction activities, pile driving and dredging. Of these, the most common is certainly shipping noise. The world merchant fleet more than doubled between 2000 and 2015 in terms of gross tonnage and now exceeds 89,000 vessels (United Nations Conference on Trade and Development 2015). Shipping is considered to have potential acoustic impacts on two different levels. The first is the impact of individual ships passing animals at relatively close range where there is potential for behavioural impacts in particular. At greater ranges, however, the ‘traffic noise’ or combined sounds of many distant ships can significantly increase the levels of ambient noise in the ocean with greatest potential for masking. This has been well documented in the North Pacific with average increases of ambient noise of around 12 dB since the 1960s and as much as 20 dB since pre-industrial times (Hilderbrand 2009).

While wind generated noise can also increase the low frequency ambient by this amount, wind noise is variable and transitory while traffic noise is not. At least some marine mammals have been shown to have compensatory mechanisms such as the Lombard effect, particularly increasing the source level of vocalisations, for overcoming wind-related ambient noise (reviewed in Hotchins & Parks 2013). Humpback whales, for example, increased the source levels of their social vocalisations in wind-elevated ambient noise (Dunlop, Cato & Noad 2014) and also switched the primary communication signal type used from vocal signals to percussive signals generated at the surface (e.g. breaches, slaps) (Dunlop et al., 2010). Interestingly, neither effect was seen as a result of noise increases from passing ships (Dunlop 2016).

3. THE BEHAVIOURAL RESPONSE OF AUSTRALIAN HUMPBACK WHALES TO SEISMIC SURVEYS (BRAHSS) PROJECT

Apart from shipping, other sources of underwater industrial or naval noise tend to be more intermittent but can have much higher source levels. One such activity is geophysical exploration using air guns, particularly prospecting for oil and gas deposits. Large survey ships tow arrays of air guns that simultaneously release compressed air rapidly into the water, thus creating a high level, broadband, impulsive sound. These percussive sounds penetrate the seafloor and bounce off various subsea rock strata, the faint reflections being collected by large arrays of hydrophones also towed by the vessel. When prospecting, the air guns are activated several times per minute with surveys continuing 24 hours per day for several weeks as the ship conducts a series of planned transects through the area of interest or ‘prospect’. Although the ‘firing’ of the individual air guns is timed to concentrate the acoustic energy downwards towards the sea floor, the horizontal radiation of energy is considerable, and there has been concern for decades about the potential impacts of this noise on marine mammals as well as other marine taxa (Richardson et al. 1995). To mitigate some of the potential effects, many jurisdictions and exploration companies themselves impose ‘shutdown’ zones around the vessel so that if a marine mammal is seen within the zone (typically 500 m to 2 km) then the air guns are temporarily powered down or shut down until the exclusion zone is clear (Weir & Dolman 2007).

While shutdown zones are designed primarily to prevent PTS, behavioural impacts are possible at much greater ranges from the source vessel (as discussed above) but little work has been done to quantify this, largely due to the logistical difficulties and expense of collecting behavioural data on whales many kilometres from the seismic vessel. In addition, if using a commercial seismic survey as the source, there is limited opportunity for carrying out proper controls, i.e. behavioural observations on whales when the air guns are not running but the ship is passing through the area. Controls are an important part of any experimental design as they account for any potential effects of the ship itself on whale behaviour as opposed to the noise from the air guns themselves (Cato et al. 2013).

In addition to the difficulties in collecting behavioural data, interpretation of the data can also be challenging. Whales (and other marine mammals) tend to have highly variable behaviour which can be influenced by many factors including general behavioural state (e.g. feeding, travelling), their social environment (e.g. the presence of other nearby whales, males searching for females, females travelling with and nursing calves; Kavanagh 2014) and other environmental factors (e.g. water depth, sea state, presence of nearby ships, ambient noise levels; Kavanagh 2014). When interpreting behaviour, these factors have to be taken into account as any change in behaviour may be due to these rather than the acoustic signal of the air guns (Ellison et al. 2012; Dunlop et al. 2015).

In 2010 the Behavioural Response of Australian Humpback whales to Seismic Surveys (BRAHSS) project was initiated (Cato et al. 2013). The project was designed to measure the behavioural impacts of seismic air guns on humpback whales as they migrated along the Australian coastline by exposing them to the sounds of air guns and measuring their behavioural changes. Humpback whales are baleen whales that feed during summer in the Antarctic and then migrate along the eastern and western Australian coasts to their winter breeding ground inside the Great Barrier Reef and off north-western Australia. Field studies for BRAHSS were conducted in September and October of 2010 – 2015 during the whales’ southward migration, when many of the females were accompanied by young calves (Table 1). These female-calf groups are likely to be the most susceptible to behavioural disturbance and hence of particular interest to the study.

Table 1. Summary of experiments. Note that the industry standard for measuring air gun chamber volume is cubic inches (in^3). Air gun capacities are total capacities used and are usually the additive capacity of several air guns in the array (e.g. the '60' in^3 air gun used in 2011 and 2013 involved the simultaneous firing of the 20 in^3 air gun and a 40 in^3 air gun). The shot interval in all experiments was 11 seconds and the tow speed was 4 knots. The 'ramp-up' treatments (2011 and 2014) were designed to give an approximate 6 dB increase in received level for each step up in air gun capacity. The Dongara experiment in 2013 was not successful due to several factors including poorer than anticipated sea conditions, increased logistical complexity as the whales were offshore, and erratic whale behaviour.

Year	Study site	Air guns (in^3)	Treatments	Treatment description
2010	Peregian, Qld	20	Active east, active north, control east, control north	Active treatments used a single 20 in^3 air gun for 60 mins towed either eastward or northward.
2011	Peregian, Qld	20, 60, 140, 440	'Ramp-up', 'constant source' and controls for each	'Ramp-up' used 3x 5 min stages (20, 60, 140 in^3) then full power (440 in^3) for 15 min. 'Constant source' used 140 in^3 for 60 mins (no ramp-up). Eastward tow only.
2013	Dongara, WA	140	'Constant source' and controls	'Constant source' as for previous experiment. Tow path generally westward.
2014	Peregian, Qld	40, 250, 500, 1440, 3130	Ramp-up over 4 steps to full power	Use of a full seismic array: ramp-up using 4x 5 min stages (40, 250, 500, 1440 in^3) then 40 min of full power (3130 in^3). Northward tow path 8.5 km offshore.
2015	Peregian, Qld	NA	Baseline only	Collection of baseline data only – no trials

Working on the migration had several advantages over working on either the feeding or breeding grounds. One was that the whales were generally travelling in a reasonably predictable direction, southwards. Another was that the whales were not feeding and, although some breeding behaviour was evident (e.g. singing, males prospecting for females), this was less energetic than on the breeding grounds. These two factors reduced, to some extent, the underlying, natural behavioural variability, making it easier to detect significant behavioural changes due to other factors such as the sounds of the air guns. A third advantage was that the whales migrated close to land at our primary field site, Peregian Beach, 130km north of Brisbane, on the Sunshine Coast (Figure 2). From previous work here, we knew that approximately 50% of the migrating whales passed within 10 km of land and could be observed from elevated land stations along the coast (Noad et al. 2004). The close proximity to land also allowed the safe use of small vessels for data collection.

BRAHSS was divided into several experiments, each following a similar study design but with progressively larger, higher level, air guns. Each experiment consisted of a series of trials where a source vessel towed an air gun or array of air guns eastwards, across the migratory path of the whales, or northwards, into the migratory flow of the whales (Table 1). Regardless of source size, we used a 'before', 'during' and 'after' design where focal groups of migrating whales were observed before, during and after exposure to air guns during each trial. For each source, approximately half the trials were 'controls' where the air guns were deployed and towed by the source vessel, but were not activated in the 'during' phase. This was necessary to determine what component of the behavioural changes observed might be due to the source vessel rather than the air guns themselves. The experiments culminated in the use of a commercial seismic exploration vessel (*RV The Duke*; Figure 3) with a 3130 in^3 full commercial air gun array.

Data were collected from several platforms (see Cato et al. 2013, 2015; Dunlop et al. 2015, 2016 for more details). Behavioural data were collected by several groups of observers at two different land stations, a 73m high hill at Peregian Beach and an elevated apartment block at Sunshine Beach (Figure 2). Observers 'focal followed' selected groups of whales as they moved through the study site and past the source vessel, recording all surface behaviours of the focal groups during each trial as well as tracking the groups using theodolites (Figure 4). Several small vessel were also used to focal follow groups of whales, maintaining a slow pursuit of the whales at a distance of 100 – 200 m as they moved down the coast. Boat-based focal follows allowed the collection of behavioural data at the level of the individual and were shown not to have a significant impact on the whales' behaviour themselves (Godwin et al. 2015; Williamson et al. 2016). The vessels also attempted to tag the whales with 'DTAGs' prior to the 'before' phase of the trial (Johnson and Tyack 2003). These suction cup tags recorded acoustic data as well as movement (magnetometers, accelerometers) and depth (Figure 5).

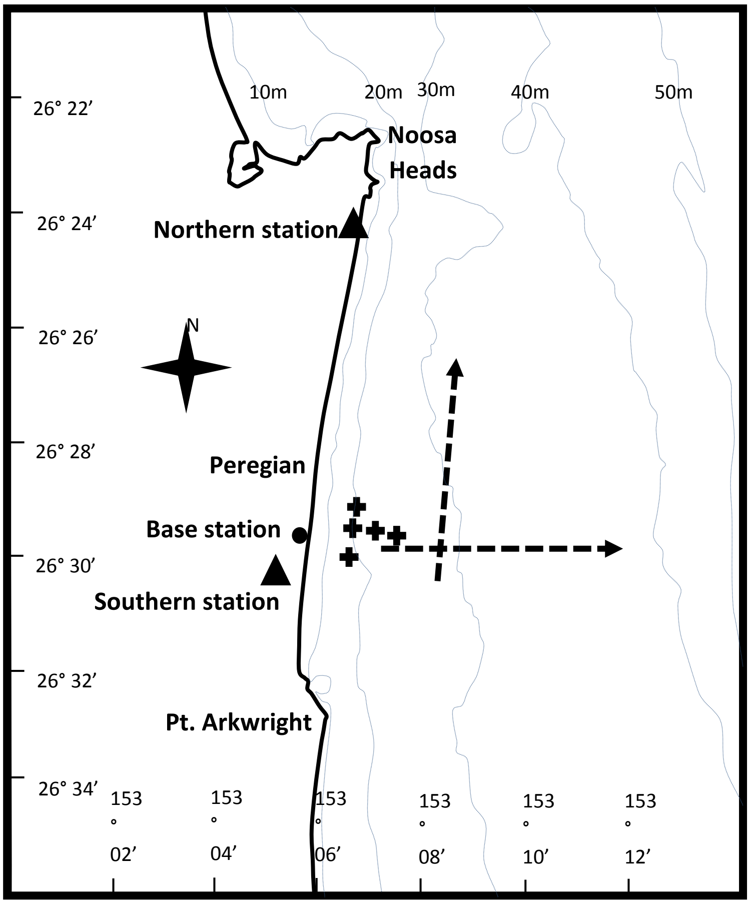

Figure 2. The Peregian study area. The hydrophone buoy array is indicated by crosses while the two transects of the source vessel used in 2010, eastwards and northwards, are indicated by the dotted arrows. Land-based visual observers were at the 'northern station' and 'southern station'. All trials were coordinated through the base station. Whale groups moved generally southwards and were usually focal-followed by land teams or small vessels from waters off Noosa Heads to waters between the southern station and Pt Arkwright.

Acoustic data were also recorded on several platforms (Dunlop et al. 2015, 2016). An array of four or five hydrophone buoys was moored off the coast (Figure 2). Each buoy was moored to an anchor clump which had a hydrophone separately attached and included a wide-band FM VHF sonobuoy radio transmitter. The radio transmissions from the buoys were received at a base station where they were recorded and used to track vocalising whales as well as measure ambient and air gun noise. A number of calibrated autonomous underwater loggers (Curtin University Centre for Marine Science and Technology) were also deployed around the area. By moving these around every few days, it was possible to develop a detailed empirical propagation model as well as accurate source level estimates for the air guns. Together, these enabled the estimation of air gun received levels at whale groups anywhere in the study area. Vertical hydrophone arrays attached to drifting buoys were also deployed near some of the focal groups at the start of air gun exposures enabling the direct measurement of received levels near the group which complimented and ground-truthed the modelled levels.

Figure 3. *RV The Duke*, the source vessel used in the last air gun experiment. The vessel conducted northward transects during the trials, but these were approximately 8km offshore, further out to sea than the path used by the smaller source vessel with the single air gun used in 2010 and shown in Figure 2. To improve manoeuvrability, *The Duke* did not deploy its long 'streamers' of hydrophones during the experiment.

In addition to the trial data, behavioural data were also collected on many other focal groups when there were no trials underway and there were neither air guns nor the source vessel in the area. These data were used to develop 'baseline' behavioural models for various response variables (e.g. swim speed, course deviance, frequency of surface slapping behaviours, dive time). All models included social predictors (e.g. group composition, interactions with other whales; Kavanagh 2014) and environmental predictors (e.g. wind speed, water depth at the groups; Kavanagh 2014). The experimental data (active trials as well as controls) were then added and tested using the predictors that best explained the variance in the baseline data. This formed a 'base' model. Treatment (active or control, air gun array capacity, path of the vessel) and received level of air gun noise were then added as predictors to see if these improved the models, i.e. whether or not the treatment type and/or received levels helped explain the variance in the behaviour (Dunlop et al. 2015, 2016).

Analysis of results are ongoing, but the results of the first two experiments can be summarised as follows. In response to a single 20 in^3 air gun, the whales decreased their dive time and the speed of their southward movement, but both changes were small. The changes were not significantly dependent on distance from the source vessel, received level or the direction of travel of the source (east or north). Interestingly, these changes in behaviour were also seen in the control groups suggesting that they were driven largely by the presence and movement of the source vessel rather than by the noise of the air gun *per se* (Dunlop et al. 2015). In the second experiment with the larger array of air guns, whales again slowed their speed of southward movement and increased their course deviation from moving south, but there was no significant change in dive time. They also, however, significantly changed course although they continued to generally move southwards. These changes were seen in both the ramp-up and constant source treatments. Again, responses were also seen in the controls although the response was less sustained (Dunlop et al. 2016).

Figure 4. Observers on Emu Mt (73m), the southern observer station at Peregian Beach. Each focal group of whales was followed by a dedicated team of observers. Horizontal and vertical bearings from the theodolites were exported directly to notebook computers running *Cyclopes* or *VADAR* software (E. Kniest, Univ. Newcastle) which calculated the position of the group in real time annotated with behaviour. Positions and behaviours were transferred in real time to the base station via the internet. This enabled the trial director at the base station to know, in real time, the positions and behaviours of all focal groups, the small vessels and the source vessel as well as the location (from the acoustic array) of vocalising animals.

Figure 5. DTAG on a whale. This was a female accompanied by a young calf (small dorsal fin visible in the foreground). Females with calves were common groups in the study area. They were often accompanied by one or two other whales ('escorts') which were usually males. Group size was commonly 2 to 4 whales.

While the results of BRAHSS to date have only included responses to relatively small air guns, the development of the field techniques and analysis framework required for a study of this scope has been significant and are as important as the results themselves. Future analyses will include the full commercial array data with its larger vessel and air guns (2014 experiment), development of a spatial explicit model of avoidance of the source, analysis of the DTAG data, and a more detailed analysis of the relationship between received level, proximity of the source and response of the whale to determine whether their response is driven more by the received level of a sound or the distance to the source.

4. CONCLUSIONS

Anthropogenic ocean noise is an important and difficult issue. The potential impacts on marine mammals and other marine taxa may be significant and biologically important while the levels of noise, particularly from commercial shipping, are likely to continue to increase globally. While progress has been made on understanding how and what marine mammals hear, additional studies are required to overcome small sample sizes in most species, and more species are required within each hearing group (Wright 2015). More focussed research is required that measures the impacts of noise on marine mammals including differences in response between species and comparisons of responses elicited by different stimuli and sound types. Still more research is required to determine how behavioural changes, masking or changes in hearing threshold translate into population level consequences. Hearing thresholds of baleen whales in particular, the only major group for which no direct audiograms are available, are also urgently needed.

The BRAHSS project is an example of the type of work required to address some of the existing data gaps. It demonstrates that it is possible to conduct structured behavioural response studies on free swimming whales using a rigorous study design, even if full experimental control is not feasible. In this paper we are unable to provide more than a summary of the field methods, analysis framework and results of this large and complex study. We hope that this study will serve not only to inform regulators, industry and the scientific community about the response of humpback whales to air guns, but will also inform the design and execution of future BRS on marine mammals.

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