Migrating humpback whales (*Megaptera novaeangliae*) do not respond to underwater construction or whale alarms off Sydney, Australia

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Table of Contents

List of Tables

List of Figures

Abstract

Humpback whales (*Megaptera novaeangliae*) migrating along the east coast of Australia are exposed to a multitude of anthropogenic activities. We investigated the effects of two types of activities migrating humpback whales are exposed to within the whale migratory corridor off Sydney; (1) fisheries mitigation and (2) underwater construction. Observational and spatial data were collected during the 2008 and 2013 northern migration off Sydney. Whale surface behaviour and directionality was compared between presence and absence of two types of 'whale' alarm (3kHz Future Oceans F3™ tone or 2-2.1kHz swept tone) and secondly in the presence or absence of underwater construction. A total of 254 tracks (146 in 2008, 108 in 2013) were collected using a theodolite. There was no detectable response to the whale alarm. Pods did not differ in directionality or surfacing behaviour whether the alarm was on or off. Whales exhibited no response to construction activities in 2008 (days with/without construction) and were no different five years post construction except that dive duration was longer in 2013. This study points to inadequacies in using acoustic alarms as a mitigation measure and is the first to assess the effects of actual underwater construction on the behaviour of migrating humpback whales.

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The 2008 data used in Chapter 2 was collected by Maryrose Gulesserian during her MPhil (The Impacts of Human Activities on Humpback Whales (*Megaptera novaeangliae)* Migrating North Past Sydney, Australia, 2009) at Macquarie University. The analysis of this data as reported in this thesis was entirely my own work.

Ethics Approval

All research was conducted under the Macquarie University's Animal Ethics Committee Animals Research Authority 2012-016. Scientific Research permit SL 100953 issued by NSW Office of Environment and Heritage.

All other research described in this report is my own original work.

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Introduction

Humpback whale entangled in fishing gear off Peru.

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1.0 Introduction

Interactions between baleen (Mysticeti) whales and anthropogenic activities continue to rise as some marine industries expand throughout the world's oceans (Hofman 1995, National Research Council 2003, 2005, O'Connor et al. 2009, Pauly 2009, Cassoff et al. 2011), in addition to the recovery of some baleen whale populations post-whaling (Carroll et al. 2011, Gales et al. 2011). Anthropogenic interactions with baleen whales are either direct or indirect. Direct anthropogenic interactions are often deliberate and include activities such as the whale watching/swimming industry in Australia (Corkeron 1995), Tonga and elsewhere (Kessler 2013), as well as commercial whaling in countries like Japan, Norway and Iceland (Moore 2014). In comparison, indirect interactions are not deliberate and often arise as a byproduct from anthropogenic activities such as underwater construction, shipping noise or entanglement in fishing gear (Nowacek et al. 2007, Cato 2010, Harcourt et al. 2014).

Regardless of intent, there are a number of anthropogenic threats impacting on the recovery of some baleen whale populations (Kraus et al. 2005, Knowlton et al. 2012, van der Hoop et al. 2013). This thesis investigated the responses of migrating humpback whales (*Megaptera novaeangliae*) towards two anthropogenic activities off Sydney, Australia. These include:

(1) Fisheries mitigation, and

(2) Underwater construction

This thesis is divided into two chapters:

Chapter 1: Migrating humpback whales show no detectable response to whale alarms off Sydney, Australia.

This chapter explores interactions between migrating humpback whales and fisheries (fishing gear) within Australian waters. This research expands upon, and significantly improves earlier work previously conducted by Harcourt *et al.* (2014), which presented one of the first *in situ* assessments of a commercially available 3 kHz acoustic deterrent device (whale alarm) intended to help prevent whale entanglement in single unit fishing gear. In Harcourt *et al.* (2014), the commercial alarm did not produce a detectable change in direction or behaviour of migrating humpback whales. A new alarm was built to assess whether the failure of the commercial alarm was due to it being too quiet in a noisy coastal area in close proximity to a major urban centre, or if the tone used was one to which the whales were indifferent. An amplifier was used to project either the 3kHz tone of a commercial alarm or a new upswept 2-2.1kHz tone adapted from Dunlop *et al.* (2013) which produced aversive responses by southward migrating humpback whales of the same population. The aim of the study was to test whether a) the more complex acoustic tone (a swept 2-2.1 kHz tone) or b) a greatly amplified existing 3kHz tone, would deter migrating humpback whale movements away from a sound source. This research helps inform the current knowledge gap regarding the use of acoustic alarms as a deterrent for baleen whale entanglement in fishing gear.

Chapter 2: Near shore construction activity did not affect the behaviour of migrating humpback whales

This chapter provides one of the first assessments of migrating humpback whales' responses to underwater construction within a migratory corridor. Construction of the Sydney desalination plant took place in 2008 and provided a unique opportunity to record humpback whale behaviour responses to underwater construction. A marine platform was placed within the narrow migratory corridor, just south of the study site. Whales were monitored on days with underwater construction (e.g. drilling and dredging activities) and days without. Whale movements were compared with whale movements tracked five years after construction. The aim of the study was to test whether underwater construction had any effects upon migrating humpback whale movements.

This research may help provide an understanding of migrating baleen whale responses to two common anthropogenic activities. Implications from these findings are likely to assist with the conservation of baleen whales with regards to interactions with anthropogenic activities.

Chapter One

Migrating humpback whales show no detectable response to whale alarms off Sydney, Australia

Humpback whale calf entangled in shark nets off Mona Vale Beach, Sydney, Australia. The shark net was fitted with a functioning whale alarm.

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Migrating humpback whales show no detectable response to whale alarms off Sydney, Australia

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2.0 Abstract

Migratory Group V (stock E1) humpback whales (*Megaptera novaeangliae*) are at risk of entanglement with fishing gear as they migrate north and south along the east coast of Australia. This study investigated the impact of two tones suitable for use as a whale alarm, on the movements of migrating humpback whales. We compared how whales responded in surface behaviour and directionality to an existing commercially available 3kHz Future Oceans F3™ whale alarm tone (5 seconds emission interval and 400m/s emission duration) and a 2-2.1kHz swept tone (8 seconds emission interval and 1.5s emission duration), with their response when there was no alarm. Observational and spatial data were collected during the 2013 northern migration from Cape Solander, Sydney, Australia. A total of 108 tracks (focal follows) were collected using a theodolite. Linear mixed effects models were used to determine the effect of different acoustic tones on whale directionality (course and absolute course change), dive duration and speed. There was no detectable response to either whale alarm tone, as pods did not differ in directionality or surfacing behaviour whether the alarm was on or off. This study is an expansion of current whale alarm technology and points to inadequacies in using acoustic alarms as a mitigation measure for migrating humpbacks during their northward migration.

3.0 Introduction

Baleen (Mysticeti) whale entanglement in fishing gear is an expensive, continuing and potentially serious problem globally (Clapham et al. 1999, Read et al. 2006, Cassoff et al. 2011). Interactions between baleen whales and fisheries are likely to increase as whale populations recover post-whaling (Carroll et al. 2011, Gales et al. 2011). Entanglements can inflict a number of life threatening injuries upon whales including restricted movement, emaciation, rope trauma, infection, tissue damage and death (Moore & Van der Hoop 2012). Unlike commercial whaling, entanglements with fishing gear serves as an unintentional source of baleen whale mortality (Cassoff et al. 2011, Moore 2014), and poses a serious threat to the continuance of species such as the Endangered North Atlantic right whale (*Eubalaena glacialis*) (Knowlton et al. 2012, Reeves et al. 2012, van der Hoop et al. 2013). Entanglement has been implicated in injury or death of many baleen whale species (IWC 2010), including the Artic bowhead whale (Reeves et al. 2012), fin whale (*Balaenoptera physalus*) (Lien 1994), minke whale (*Balaenoptera acutorostrata)* (Northridge et al. 2010, Song et al. 2010), humpback whale *(Megaptera novaeangliae)* (Lien 1980, Neilson et al. 2009) and southern right whale (*Eubalaena australis*) (Best et al. 2001). Entanglement in fishing gear may also be a limiting factor in the recovery of Critically Endangered baleen whale species such as the Western gray whale (*Eschrichtius robustus*) (Bradford et al. 2009).

Preventing whale entanglement in fishing gear has involved a variety of mitigation measures including gear modification and seasonal fishery closures (Knowlton & Kraus. 2001, Kraus et al. 2005). However more long-term mitigation measures have included the use of acoustic alarms in attempts to try and prevent whale entanglement in fishing gear (Lien 1980, Lien et al. 1994). Whale alarms function as an alerting mechanism to warn whales of fishing gear presence and by inference, reduce the risk of entanglement. As whales communicate using low frequency vocalisations (Ketten 1997, Ketten 2012), acoustic alarms might be a potential way to prevent whale entanglement in fishing gear. Lien (1980) was the first to report the use of simple sound producing devices placed on nets to alert humpback whales to fishing gear presence off Newfoundland, Canada. To prevent entanglement, Lien (1992) suggested whales must notice the sound source and also associate it with nets. Initial experiments by Lien (1980; 1990; 1992) found some whales did notice the sounds and moved away while others were attracted to the devices. Since Lien's initial work more than 30 years ago, alarm technology has improved, however the success of whale alarms in actually preventing baleen whale entanglement has been little studied. Acoustic alarms have had mixed success in mitigating entanglement for odontocetes such as dolphin and porpoise species (Barlow & Cameron 2003, McPherson 2011, Berg Soto et al. 2013, Dawson et al. 2013). Yet until recently there has been no systematic research *in situ* to test the efficiency of whale alarms in deterring whale entanglement from fishing gear (Jefferson & Curry 1996, Harcourt et al. 2014).

A systematic assessment of a singled moored, commercially available low frequency whale alarm (3 kHz Whale Pinger® (135dB (+/-4 dB re. 1 μPa at 1 m)) on the movements of migrating east coast Australian humpback whales *(Megaptera novaeangliae)* found that whales showed no detectable response to the alarm, suggesting a simple 3kHz low frequency alarm is unlikely to deter migrating humpback whales from approaching fishing gear (Harcourt et al. 2014). This raises concerns as these alarms are fitted within both the Queensland Shark Control Program (QSCP) and the New South Wales Shark Meshing Program (SMP) (Reid et al. 2011, Sumpton et al. 2011) and suggests there is a need to investigate alternatives.

Migratory east coast Australian humpback whales encounter a range of fishing activities as they migrate along the east coast annually from their high latitude feeding grounds to their low latitude breeding grounds (Chittleborough 1965). Types of fishing gear that cause whale entanglements within Australian waters include longlines, gillnets, shark nets and single units like lobster and crab pots (Groom & Coughran 2012). Although the east Australian shark net (bather protection) programs in Queensland and New South Wales are fitted with whale alarms, they are experiencing ongoing humpback whale captures that inevitably result in substantial media attention, suggesting the alarms are not deterring all whales. Some of these have been fatal with the whales entangled in nets fitted with functioning whale alarms, the same model as those tested by Harcourt *et al* (2014), who found propagation of the commercial alarm was poor and possibly not strong enough to be detected by whales from far enough away. Increasing humpback whale populations will inevitably lead to increased interactions with fishing gear, highlighting the urgent requirement to find a suitable aversive sound for use as a bycatch mitigation tool for fishers.

Since the end of all commercial whaling within Australian waters, the east coast humpback whale population (Stock E1, Group V (Gales et al. 2011)) remains under Australian Federal

Government protection (EBPC Act 1999) and is currently recovering at 10.9% per annum (Noad et al. 2010). This suggests that the problem of entanglement will increase as there are more whales migrating up and down the east coast of Australia, and as fishing activity will likely not decrease, the need for an effective alarm is even greater.

A tone within the frequency range of humpback whale vocalisations reliably induced a behavioural response in humpback whales of the same population in southern Queensland waters during their southern migration (Dunlop *et al.* 2013), suggesting this tone might potentially work as an alarm. Accordingly we assessed whether this tone or a louder version of the existing alarm may be more effective at altering the path of migrating whales and thereby reducing the chance of entanglement. We used an amplifier to project either the existing 3kHz tone, or this upswept 2-2.1kHz tone adapted from Dunlop *et al.* (2013). The new alarm (representative of a single lobster/crab pot where whale alarms are typically fitted to) was moored in the middle of the humpback whale migratory corridor off Sydney, Australia. The aim of the study was to test whether movements of north migrating whales were influenced by either of these alarm tones in deterring migratory humpback whale from swimming into the alarm, i.e. a simulation of entanglement.

4.0 Methods

4.1. Study Site

The study was conducted at Cape Solander in Botany Bay National Park, Sydney Australia (34° 01’S, 151° 14’E) (Fig. 1). The observation platform was located 30 metres above sea level and has been used for whale observations for over 17 years.

4.2. Whale Alarm

A fixed mooring with a surface float was installed 1.3 km offshore of the observation platform in 53 m of water with the prototype whale alarm secured at 5 m depth. The whale alarm consisted of a rolled aluminum housing surrounding a single high-powered speaker (Rated power: 75W Max power: 150W, Impedance: 8 Ohm, Freq response: 800Hz-20kHz, sensitivity 110dB at 1m with 1 W input into the replay system), battery pack and an iPod nano® at a depth of 5 m. This depth is similar to that used by the fishing industry to deter whales from entanglement in set nets and lines (Erbe & McPherson 2012, Harcourt et al. 2014). The whale alarm mooring was anchored in the midpoint of the peak migration route recorded in the years 2006-08 (Gulesserian et al. 2011).

A randomised playlist was preset on the iPod nano® which played one of two tones or a control of no tone for 11 hours each day (07:00-16:30, daylight hours). The two tones were (1) a 2-2.1kHz swept tone (8 seconds emission interval and 1.5m/s emission duration, adapted from Dunlop *et al.* (2013) or a (2) Future Oceans F3, 3kHz Whale Pinger® tone (135 dB (+/- 4 dB re.1 μPa at 1 m), 5 seconds emission interval and 400ms emission duration). Both tones are within the frequency range of humpback whale vocalisations, therefore we assume both tone were audible (Dunlop et al. 2013). The observer who was tracking the whale paths did not know the status of the alarm.

4.3. Data Collection

Data were collected between 28 June 2013 and 4 August 2013, thus coinciding with the peak of the northern migration (Nicholls et al. 2000, Vang 2002, Gulesserian et al. 2011) using the method described in Harcourt *et al.* (2014). Observations were made using the naked eye and 7 x 50 magnitude binoculars. All data were recorded using a theodolite set up on the Cape Solander observation deck that stands 30 metres above sea level. A Sokkia DT510A theodolite (with a precision of ± 5 seconds of arc and 30x magnification, set up at 1.5 metres high) was connected to a laptop computer running custom written software *VADAR©* (Version 1.51.02 Eric Kneist, University of Newcastle, Australia). The theodolite simultaneously measured horizontal and vertical angles to a target that was measured from a known reference object, Cape Banks (the headland north of the field site).

At least two people constantly scanned to the south for approaching humpback whale pods. A pod was defined as either a lone whale or a group of whales. Pods were selected as far south as possible, this allowed the approach to the whale alarm to be recorded. All whales that passed through the study site were on their annual northern migration and therefore each observation was considered independent. Once a pod was seen, a focal animal, distinguishable by the natural variation in markings and dorsal fin shape, was chosen to track within a pod. We recorded every surface event for the focal animal, as well as any associated behaviour with every surfacing, from the moment the pod was first sighted until it left the study area (>4000m north of the theodolite) or could no longer be seen. Common causes of poor visibility included intense sunlight and mist. Once a pod moved out of the study site, the next southernmost pod was selected for tracking (if present). We monitored all vessels using a 15 minute scan of vessel activity (Martin & Bateson 1998).

We made observations from dawn till dusk (subject to daylight usually 0620-1720 hours) when weather conditions were favourable (no rain and Beaufort of <5). We recorded weather conditions throughout the day and included: Beaufort, swell, cloud coverage and rain. Only Beaufort recordings of 1-6 from a 0-12 scale were considered for this study.

4.4. Whale Alarm Recordings

To examine the range at which the prototype whale alarm was detectable, we made acoustic recordings as described in Harcourt *et al.* (2014). We made recordings of each tone at two locations, (1) the mooring site, 1.3km offshore of the Cape Solander headland in Botany Bay National Park, Sydney Australia (34° 1' 22.548" S, 151° 14' 44.664"E) and (2) Sydney Institute of Marine Sciences (SIMS), Chowder Bay, Sydney, Australia (33° 50' 18.8232" S, 151° 15' 20.883" E). We used a HTI 554036 hydrophone attached to 30 metres of line that recorded directly onto M-Audio Micro Track 24/96 Professional 2-Channel Mobile Digital Recorder.

For all open-ocean/*in situ* testing, we created a grid over the mooring that was 300m x 300m with 50 m intervals, and used a Garmin GPSMAP® 78sc GPS was used to locate the start of each transect line. At the start of a transect line, the boat motor was switched off and the hydrophone was lowered to 30 metres and recording started. We selected transect lines based on wind conditions that would allow drifting over an entire transect, and once recordings commenced the boat was left to drift along the entire transect. Recordings ceased once the boat had reached the end of the transect line. The boat then motored up to the start of the new transect and the recording process was repeated.

At SIMS, Chowder Bay, source levels were recorded at one, three and five metres away from the prototype whale alarm and a Future Oceans F3, 3kHz Whale Pinger®. Measurements were taken in calm weather conditions (Beaufort 1). Recordings were taken at one and two-metre depths and background noise included boats, underwater chain and snapping shrimp.

4.5. Data Extraction and Analysis

All observational information including the exact time of each surface and behaviour (±0.5second) were recorded and exported directly onto a laptop running *VADAR*© (2013). This included all focal follows, focal follow summaries, observation information and raw observations for every day and every pod. Only tracks that were at least of 15 minutes duration, that included multiple (two or more) dives, and that passed within 1000 metres of the alarm were included in the analysis.

We used two measures of direction: the bearing between consecutive surfacing in relation to north (course from north), and the change in turn angles between each surfacing (absolute course change). We used the last respiration before each dive and the first after a dive to calculate dive duration (measured in seconds). After a dive, whales remained at the surface respiring a number of times. To avoid calculating sequential surfacing respirations after a dive, all surfacing events less than 120 seconds (<two minutes) were excluded from the analysis. Speed was measured as the time in seconds to travel the distance in metres between consecutive sightings (m s^{-1}).

To measure the potential effects of the alarm, we assessed whale behaviour between two treatments (2-2.1kHz tone and 3 kHz tone) and a control (Silent/no tone). Based on our *in situ* measurements similar to those conducted by Harcourt et al. (2014), we assumed all whales that passed within 1000 metres of the alarm were likely able to hear the tone. This assumption was made on the basis of anatomical evidence and the frequency at which humpback whales produce song units (males only) and social vocalisations (Ketten 1992, Ketten 1997, Dunlop et al. 2008, Dunlop et al. 2013).

To test for differences between treatments, we used linear mixed-effects models with focal follows as the random effect to account for individual differences and four response variables. These were course from north (degrees), absolute course change (degrees), dive duration (seconds), and speed (m s^{-1}). As we couldn't observe whale behaviour underwater, these four behavioural metrics were chosen on the basis of being observable through the methodology used in this study. If the alarm was to have any effect on an individual whale, we may expect a change in whale speed, which may differ to its speed prior to entering within the acoustic range of detectability. Similarly, if whales responded to the alarm we might also see changes in respiration, with whales surfacing more or less frequently or changes in directional movements with whales either turning rapidly toward the alarm or moving away from the area. Linear mixed effects models are used for data that are collected and placed within groups. The use of linear mixed-effects models allowed us to explore differences in individual whale behavioral responses (random effect) within each treatment (fixed effect). Whale behavioural responses were grouped based upon the tone they were exposure to.

A cosine and logistic transformation was applied to all circular (directional) data (course from north and absolute course change). For all statistical analyses, the null hypothesis was rejected if $p < 0.05$. All statistical analyses were performed using the nlme library in the statistical software package R (Pinheiro et al. 2014) (R Foundation for Statistical Computing).

5.0 Results

A total of 108 focal follows were collected over 300 hours of observation. Observations were made for 12 days while the source was silent (control), 10 days for the upswept 2-2.1kHz tone, and 11 days for the 3 kHz tone. Over half (52%) of focal follows were collected within the control treatment (57). Of the remaining, 28 focal follows were collected within the 2-2.kHz treatment (27%) and 23 within the 3kHz treatment (21%). Through *in situ* testing, we found both tones were audible up to 1000m for a Beaufort of 5, the highest wind force within which observations of whale responses took place. The surface plots of whale movements within the two treatments and control are visually similar (Fig. 2 a, b, c).

The direction whales were heading relative to north did not differ between the control and treatments (see Table 1, Fig 3 a and Fig 4 a). Whales appeared to follow a similar northeast path as they passed through the study site. Similarly, whales showed no difference in absolute course change between treatments (see Table 1, Fig 3 b and Fig 4 b). Collectively, these results suggest whale movements relative to north and directional movements are not a function of the alarm but most likely a result of topography.

Whale dive duration (downtime) was different between the control tracks and treatments only when generalized linear models were applied (Table 1, Fig 3 c). However, when taking into account individual whales as the random effect, mixed effects models suggest whales showed no difference in dive duration irrespective of the two treatments and the control (Table 1). Whale speed did not differ between the two treatments (Table 1, Fig 3 d). The mean speed across both treatments and the control were similar, 2kHz: 2 m s^{-1} (SD= 1.08 m s^{-1}, n= 28), 3kHz: 2 m s^{-1} (SD=1.08 m s^{-1}, n= 23) and control: 2 m s^{-1} (SD= 1.17 m s^{-1}, n = 57). These results suggest that the alarm had no effect upon whale speed. There was also no effect of distance to the alarm (Figure 3 e).

6.0 Discussion

Baleen whale entanglement in fishing gear is an international problem likely to increase with the growth of fishing effort alongside the recovery of some whale populations post-whaling (Read 2008, Pauly 2009). Commercial whale alarms, designed to alert whales to fishing gear presence, were recently tested *in situ* by Harcourt *et al.* (2014) and were found to be an ineffective means of preventing baleen whale entanglements in single unit fishing gear for whales during their northern migration. They suggested the tone might be too faint in a noisy ocean or that the whales might have been indifferent to the monotone commercial alarm. The current study furthered the work by Harcourt *et al.* (2014) by testing both a more complex tone and by amplifying the existing 3kHz tone. We found whales showed no detectable difference in directionality, speed or dive duration between treatments, similar to the results found by Harcourt *et al.* (2014). Interestingly, whales showed no response to the swept tone adapted by Dunlop *et al.* (2013), previously documented to evoke an aversive behavioural response when played from a boat. Despite using a more complex and powerful tone, with an increased range of acoustic tone propagation and a lower frequency range, these results suggest that this particular design of an acoustic alarm is ineffective at deterring migrating humpback whales from entanglement in single unit fishing gear.

This study amplified an existing 3kHz tone to enhance alarm detectability to deter baleen whale entanglement in fishing gear. Increases in projection levels of the simple 3kHz tone doubled (1000m) the theoretical range of detectability as seen from the commercial alarm (500m) (Harcourt et al. 2014). Increases in projection levels meant that the 3kHz tone was assumed audible for the majority of humpback whales that passed through the study site. Increases in tone propagation also decreased the likelihood of the 3kHz tone being constantly masked by anthropogenic (e.g. shipping) and biological or physical contributors (e.g. snapping shrimp, wave dependent noise) to ambient levels within the study site environment (Cato & McCauley 2002).

The use of a more complex tone was emitted at the same amplification level as the 3kHz tone to enable direct comparison between treatments. This tone, which consisted of a lower frequency and longer emission duration, was therefore predicted to have increased the likelihood of the alarm's detection compared with the shorter 3kHz tone. We assumed that whales were able to detect the alarm (both tones) based upon anatomical evidence and the frequency at which humpback whales produce song units (males only) and social vocalisations (Ketten 1992, Ketten 1997, Dunlop et al. 2008, Dunlop et al. 2013). In the absence of direct measurements of humpback whale hearing, the experiments by Dunlop *et al.* (2013) demonstrated that the humpback whales responded to 2 kHz tones for received SNRs that are consistent with what would be expected for mammal hearing in general, i.e. they responded even though the sounds were close to the audible limit. Hence we assume that the whales are able hear what humans can hear for sounds in the frequency band of their own sounds. No amount of measurements of received levels will improve this without the assumption that humpback whales hear like other mammals, but listening gives a direct comparison.

In experiments by Dunlop *et al.* (2013), an individual humpback whale fitted with a Dtag altered their behavioural in response to the 2kHz swept tone estimated to be audible from 880 metres (signal level RL of 101dB re.1 μPa and SNR of 8dB), with the female humpback whale (within a female-calf group) initially changing course at 660 metres (signal level RL of 105dB re.1 μPa and SNR of 13dB) away from the source vessel (Dunlop *et al.* 2013). However, this study mainly consisted of female-calf and female-calf-escorts while the northward migrating whales in our study were adult individuals and pods. Southward migrating mothers may have been more cautious and responsive to the tone as a protective strategy while they protect their calves. These whales moved away and offshore in response to the upswept tone (Dunlop *et al.* 2013). Despite this, it seems likely that the whales in our study were capable of detecting the alarm tone but we still saw no difference in the behaviour and or direction of movement of the whales.

Despite placing a whale alarm directly within a migratory corridor off Sydney, this study found that northward migrating humpback whales continued passing close to the sound source for both whale alarm tones. Assuming acoustic detectability, it is possible that whales may have been 'alerted' but just did not deviate away from the alarm. Initial experiments by Lien (1980; 1990; 1992) demonstrated that in different cases whales were both attracted and deterred from acoustic devices. In some instances whales both slowed and turned in the direction of the sound to investigate, while others turned away from the sound source and increased speed (Lien 1980, Lien et al. 1990a, Lien et al. 1990b, Lien et al. 1992). These trials, however, were only conducted on humpback whales within feedings areas as compared to the humpback whales in mid migration tested in our study. Baleen whales devote a large proportion of time and energy each year to migrate (Corkeron & Connor 1999, Silva et al. 2013). Often these migrations involve competitive breeding and births, all while moving with direct (or near direct) and precise navigational orientation (Corkeron & Connor 1999, Horton et al. 2011, Waugh et al. 2012). Unlike migrating humpback whales, feeding humpback whale behaviour may be different, involving active foraging and exploring of the environment (Stimpert et al. 2012). Feeding whales may have been more mindful to any acoustic presence as a result of foraging in comparison to migrating humpback whales which traverse an immense distance over a short period of time and may not pay attention to the alarm or associate it with a threat (Noad & Cato 2007, Silva et al. 2013). Results from this study suggest even if whales were alerted by the alarm, they did not alter behaviour or course, and continued on their northward journey.

Humpback whales moving along the east coast of Australia are exposed to many different natural and anthropogenic sounds during their migration (Cato & Bell 1992, Cato & McCauley 2002, Cato 2010). We are still unsure if humpback whales make a connection between the alarm and the presence of fishing gear (supported by no evidence that they avoid fishing gear). However it would be reasonable to assume that whales migrating through this area have become accustomed to a wide variety of noises, and so the alarm may have been simply another part of this modified acoustic environment (Dunlop et al. 2010). Ambient noise along the east coast of Australia has the potential to mask the alarm's output (Cato & McCauley 2002, Erbe & McPherson 2012). This was possible in the waters off Sydney, where the alarm was placed, as there was a high level of shipping activity, contributing noise to the acoustic environment. Anthropogenic noise, in addition to natural sound sources has been a concern for other acoustic alarm studies. High levels of anthropogenic noise has the potential to reduce the range of the acoustic alarm tone is likely to vary among different environments and may be influenced by coastal geomorphology (Erbe & McPherson 2012). The alarm tones used in this study were therefore propagated at source levels well above the currently available commercial alarms in an effort to ensure this factor did not affect our assessment of the effect of the emitted tones on whale movements. In order to be effective, acoustic alarms should be audible in even the most unfavorable of ambient conditions (Harcourt et al. 2014). Our results suggest the effectiveness of acoustics alone as a deterrent to entanglement is subject to a number of limiting factors including local ambient noise.

This study, along with recent research (Harcourt et al. 2014), provides some of the first evidence from *in situ* testing of current whale alarm technology. As the east coast humpback whale population increases so will the potential for more entanglement. Future research is needed to determine what type of acoustics is needed to generate a response in humpback whale behaviour. Further research examining the potential of an array of complex acoustics, incorporating lower and higher frequency tones, as well as swept and modulated tones, with longer emission durations, conducted *in situ*, on northward migrating, southward migrating, and feeding humpback whales is required in order to reduce the impact of entanglement. Once this is determined, trialing the use of new technology will be required on other fishing gear types (e.g. longlines, gillnets, shark nets) currently deployed in areas where entanglement is a problem. Preventing the unintentional mortality of baleen whales should be of great interest and responsibility within the global fishing community, world Governments, NGOs and the scientific community. Future efforts to reduce entanglement should be at the forefront of baleen whale conservation biology research.

7.0 Acknowledgments

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We would like to thank Dr Simon Northridge, Dr Peter Corkeron and Prof Douglas Wartzok for reviewing early drafts of the manuscript. We thank Maryrose Gulesserian, Eric Kneist (author of VADAR), Wayne Reyonlds, the Cape Solander Whale Migration Study and the Kamay Botany Bay National Park Staff for facilitating the field research. Thank you also to Andrew Boomer for construction of the whale alarm, mooring assemblage, deployment, retrieval and hydrophone testing along with Andrew Irvine, Phil McDowall and Andre Steckenreuter.

Chapter One: Tables and Figures

1. Table legends

1.1. **Table 1: Results from linear mixed effects models for all four-response variables.**

There was no difference in whale directional movements (course from north (degrees) and absolute course change (degrees)) between treatments. Whales did not show any difference in speed (m s^{-1}) or dive duration (seconds) between treatments. This table details the treatment type, parameter estimate, standard error, t-value and p-value for each response variable. Course from north (degrees) (random effects (SD); intercept: 0.6212445, residual: 1.390292), absolute course change (degrees) (random effects (SD); intercept: 0.578817, residual: 2.794491), dive duration (seconds) (random effects (SD); intercept: 0.3426297, residual: 0.310925) and speed (m s^{-1}) (random effects (SD); intercept: 0.2801382, residual: 0.3664969).

1.2. Table 1

Response variable	Treatment	Parameter estimate (value)	Standard Error	t-value	p-value
Course from north (degrees)	Control	3.458925	0.1106049	31.272816	0.0000
	2-2.1kHz	-0.142243	0.1869847	-0.760723	0.4486
	3kHz	-0.082737	0.1831412	-0.451767	0.6516
Absolute course change (degrees)	Control	3.947045	0.1697343	23.254259	0.0000
	2-2.1kHz	-0.524162	0.2762372	-1.897506	0.0607
	3kHz	-0.398503	0.3002628	-1.327180	0.1849
Dive duration (seconds)	Control	5.686731	0.04559301	124.72813	0.0000
	2-2.1kHz	0.022081	0.08204794	0.26912	0.7884
	3kHz	0.060787	0.05576328	1.09010	0.2761
Speed (m s^{-1})	Control	0.5362088	0.04069357	13.176743	0.0000
	2-2.1kHz	-0.0676051	0.07136623	-0.947298	0.3458
	3kHz	-0.0241876	0.05872111	-0.411907	0.6805

Chapter One: Figure Legends

Figure 1: Location of study site, Cape Solander, Sydney, Australia.

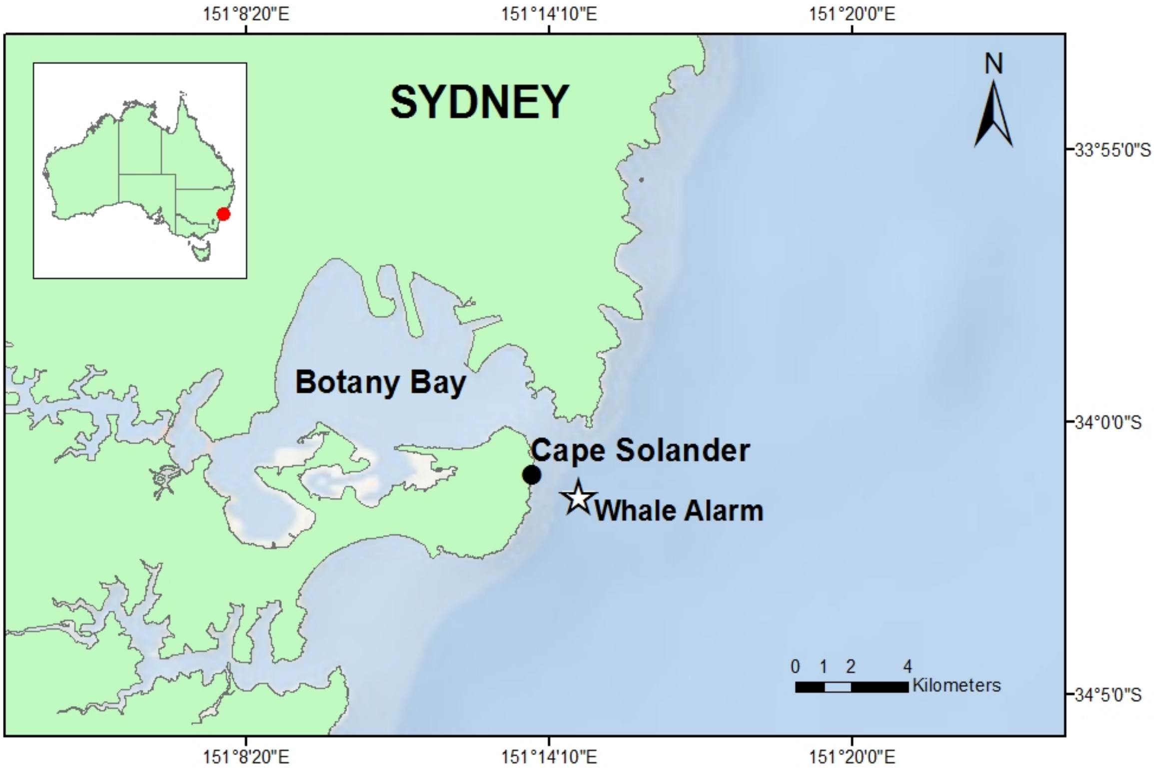
Figure 2: All tracks that passed within 1000m of the alarm mooring. Whale alarm location indicated by star (depth of 53 metres). All focal follows that passed through the study site when the alarm was a) off (control) and focal follows when the alarm emitted either the b) 3kHz tone or c) 2-2.1 kHz swept tone. Each dot represents a single whale surfacing along individual focal follows. The triangle represents the location of the theodolite. A black 1000m radius around the alarm mooring represents the likely acoustic range of detectability.

Figure 3: Results from directional data: a) course from north (degrees), b) absolute course change (degrees) and non-directional data: c) dive duration (min) subset of all surfaces >=120 seconds, d) speed (m s^{-1}) and e) average distance to the alarm (km).

Figure 4: Directional data focal follow distribution a) course from north and absolute b) course change for each individual focal follow.

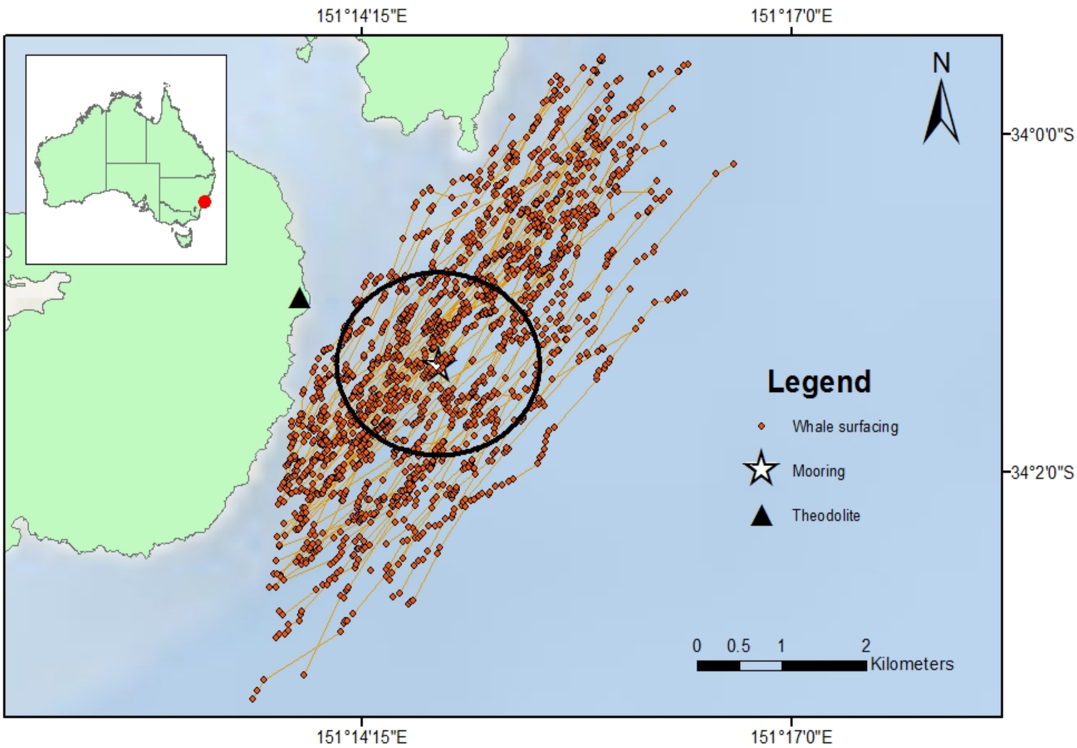
Chapter One: Figures

1.1. Figure 1

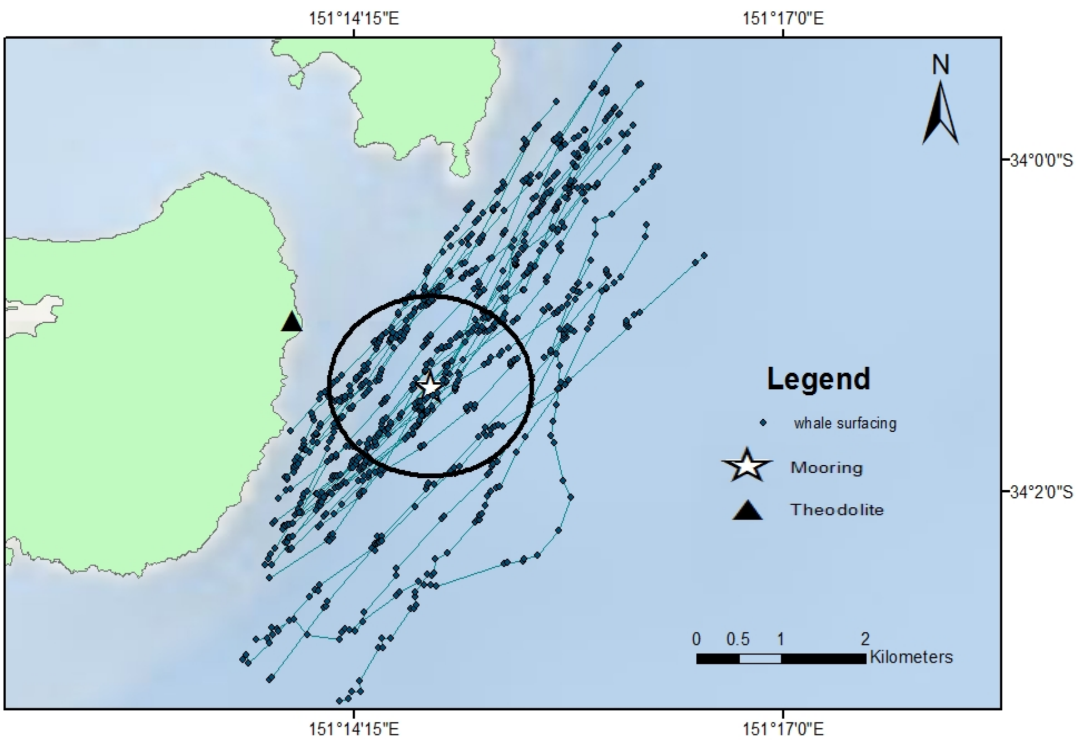


1.2. Figure 2 a and b

a

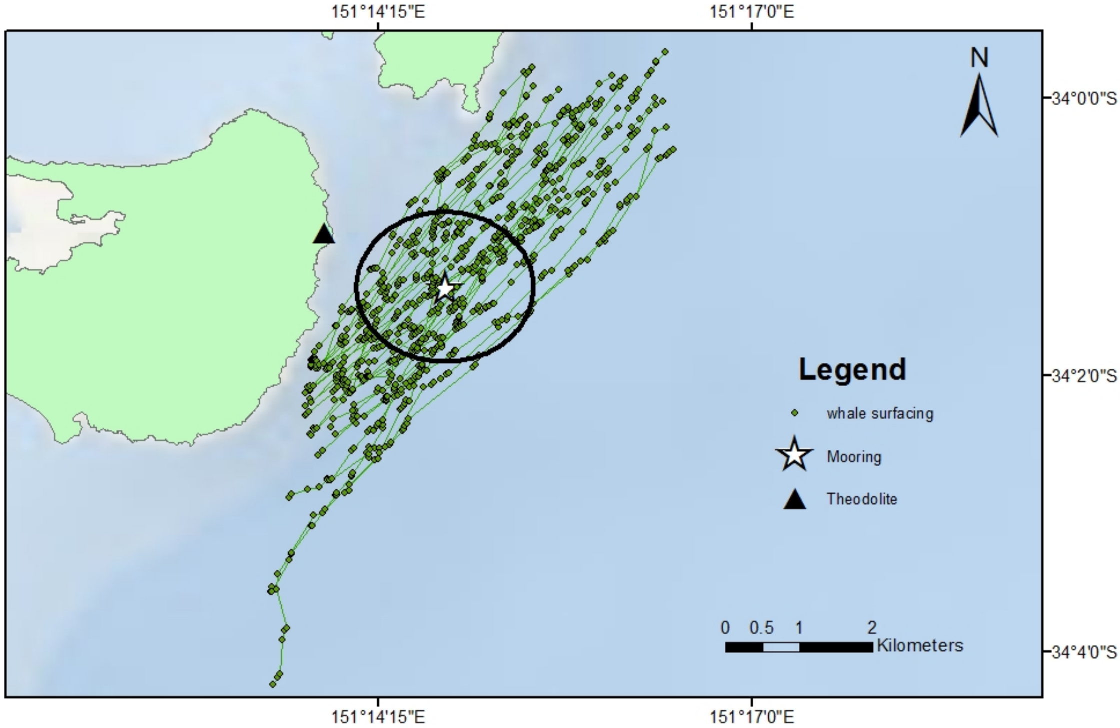


b

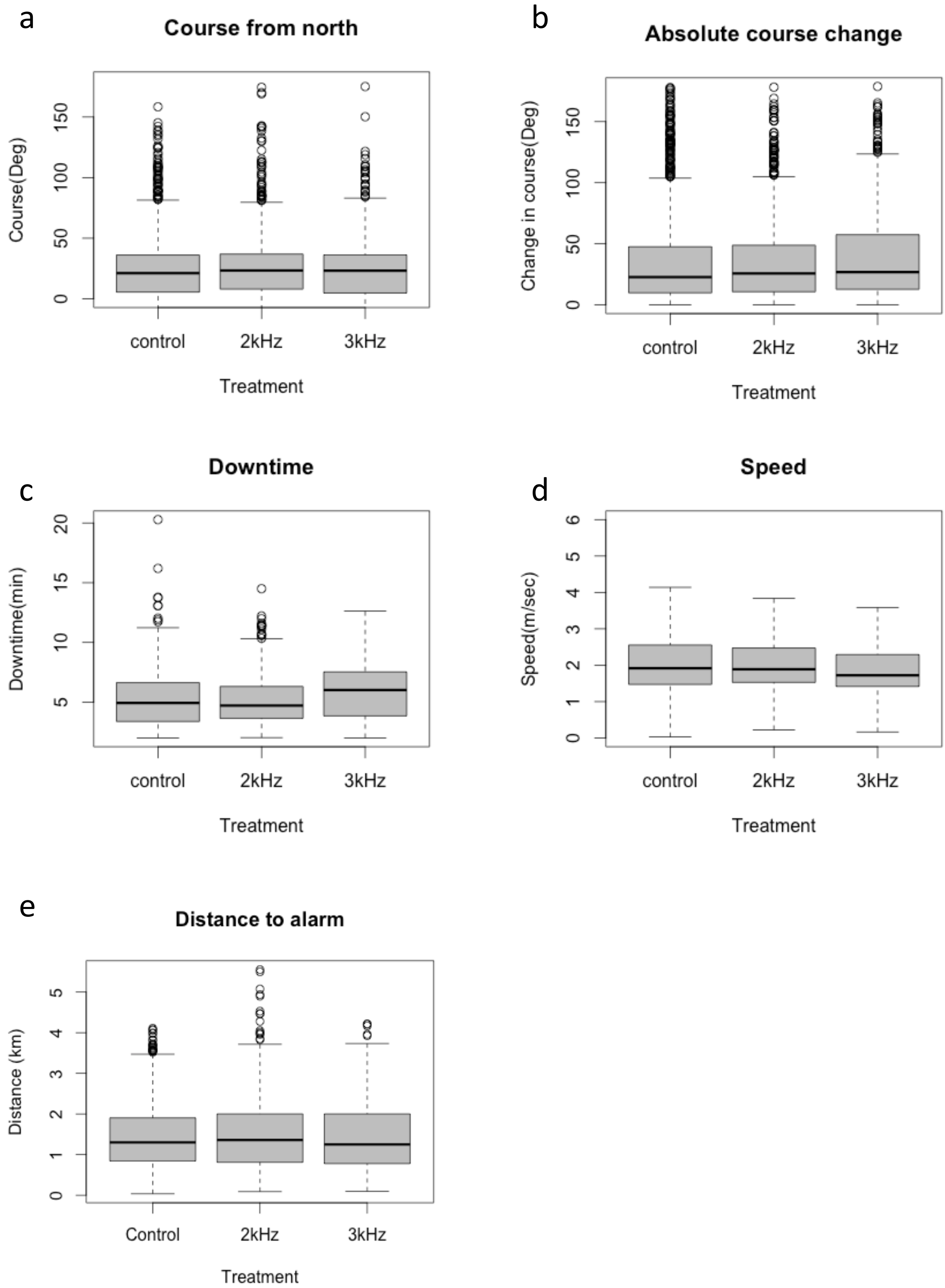


1.3. Figure 2 c

c

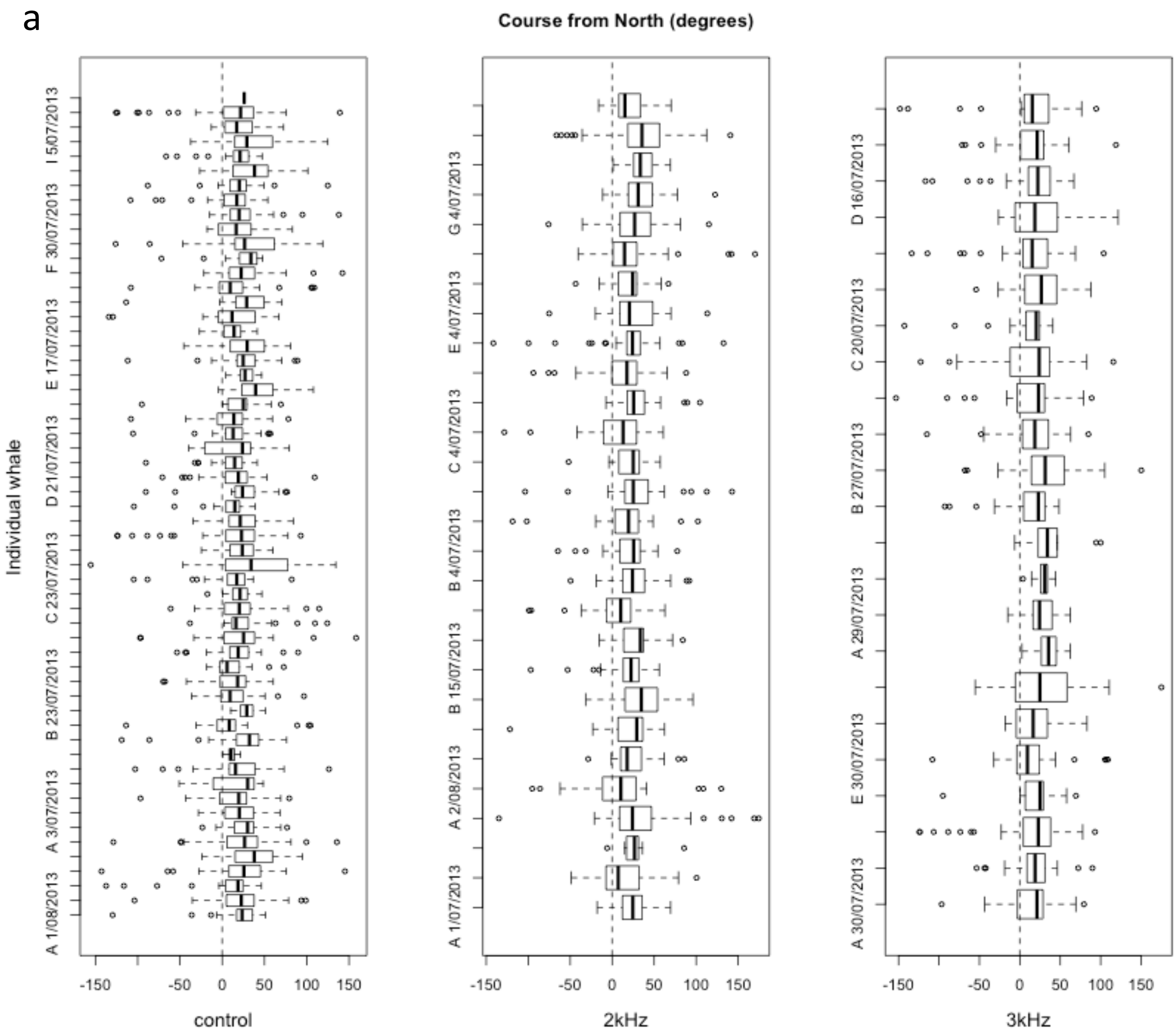


1.4. Figure 3

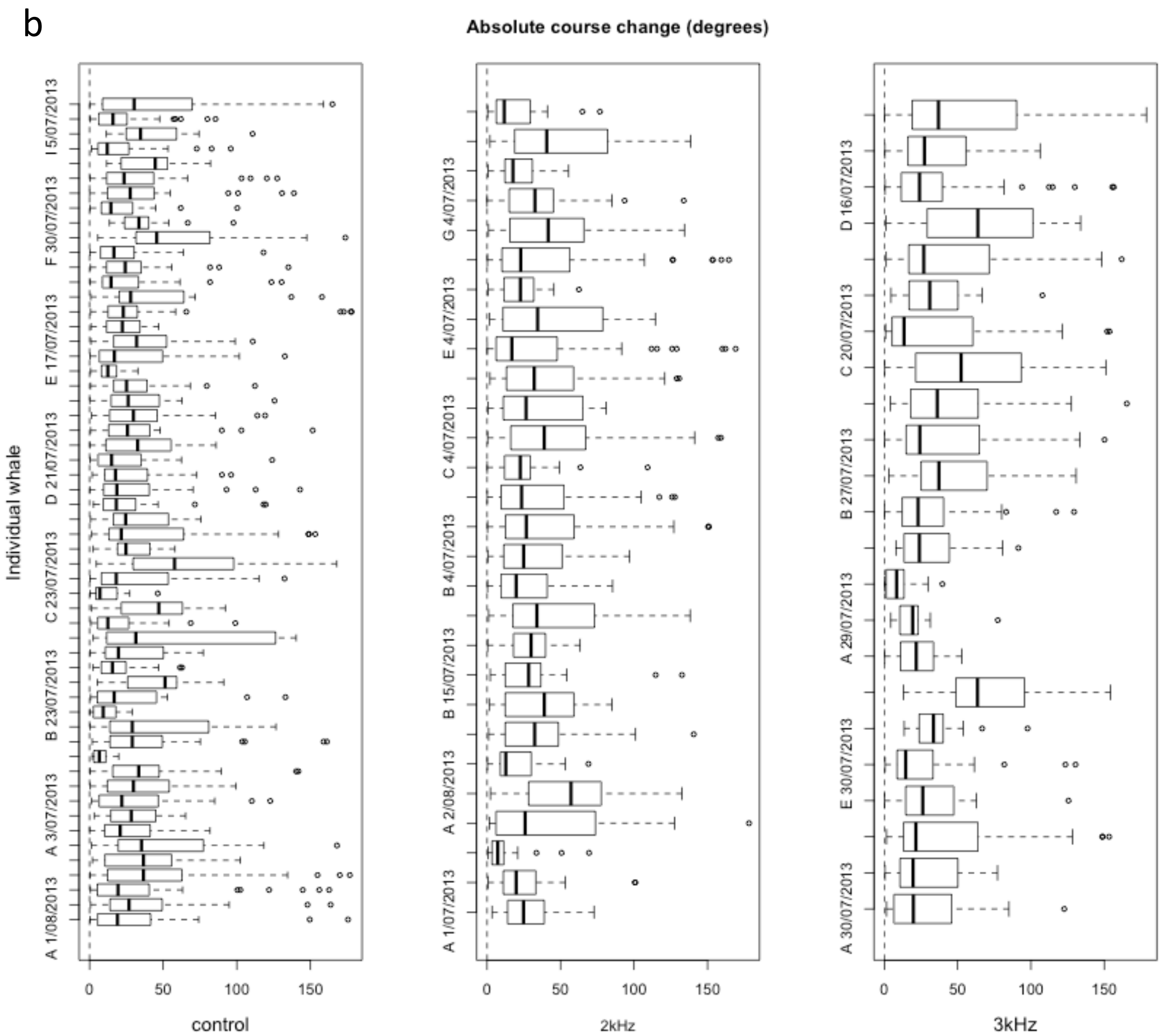


a
Course from north
Course(Deg)
0
50
100
150
control
2kHz
3kHz
Treatment
b
Absolute course change
Change in course(Deg)
0
50
100
150
control
2kHz
3kHz
Treatment
c
Downtime
Downtime(min)
5
10
15
20
control
2kHz
3kHz
Treatment
d
Speed
Speed(m/sec)
0
1
2
3
4
5
6
control
2kHz
3kHz
Treatment
e
Distance to alarm
Distance (km)
0
1
2
3
4
5
Control
2kHz
3kHz
Treatment

1.5. Figure 4 a


a
Course from North (degrees)
Individual whale
A 1/08/2013
A 3/07/2013
B 23/07/2013
C 23/07/2013
D 21/07/2013
E 17/07/2013
F 30/07/2013
I 5/07/2013
control
A 1/07/2013
A 2/08/2013
B 15/07/2013
B 4/07/2013
C 4/07/2013
E 4/07/2013
G 4/07/2013
2kHz
A 30/07/2013
E 30/07/2013
A 29/07/2013
B 27/07/2013
C 20/07/2013
D 16/07/2013
3kHz
-150
-50
0
50
100
150

1.6. Figure 4 b


b
Absolute course change (degrees)
Individual whale
A 1/08/2013
A 3/07/2013
B 23/07/2013
C 23/07/2013
D 21/07/2013
E 17/07/2013
F 30/07/2013
I5/07/2013
control
A 1/07/2013
A 2/08/2013
B 15/07/2013
B 4/07/2013
C 4/07/2013
E 4/07/2013
G 4/07/2013
2kHz
A 30/07/2013
E 30/07/2013
A 29/07/2013
B 27/07/2013
C 20/07/2013
D 16/07/2013
3kHz
0
50
100
150

Chapter Two

Near shore construction activity did not affect the behaviour of migrating humpback whales

Humpback whales migrating north through the migratory corridor off Sydney, Australia. Whales pictured moving around the Sydney desalination plant construction platform where underwater construction took place.

Near shore construction activity did not affect the behaviour of migrating humpback whales

Running Head: Underwater construction does not affect migrating humpback whales

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8.0 Abstract

Humpback whales (*Megaptera novaeangliae*) migrating along the east coast of Australia are exposed to a multitude of anthropogenic activities. We investigated the effects of under water construction arising from the development of the Sydney desalination plant within the whale migratory corridor off Sydney, Australia. Observational and spatial data were collected during the 2008 and 2013 northern migration from Cape Solander, Sydney. Whale surface behaviour and directionality was compared in the presence or absence of underwater construction. A total of 202 tracks (146 in 2008, 56 in 2013) were collected using a theodolite. Linear mixed effects models were applied to determine the effect of underwater construction on whale directionality (course and absolute course change), dive duration and speed and to also show the effects of distance to construction activities (construction, no construction and post construction). Whales exhibited no response to construction activities in 2008, with similar behaviour on construction and no construction days. Behaviour was also monitored five-years post-construction, and analyses showed that with the exception of longer dive durations in 2013, whale behaviour did not change. This study is the first to assess the effect of underwater construction on the behaviour of northerly migrating humpback whales off Sydney, Australia.

Keywords: anthropogenic, underwater construction, noise, drilling, *Megaptera novaeangliae*

9.0 Introduction

Interactions between cetaceans and anthropogenic activities in the ocean are likely to increase as these activities become more prevalent (Richardson et al. 1995, Wilcock et al. 2014). These activities include underwater construction (e.g. dredging, drilling, explosives, pile driving), vessel activity (e.g. shipping, tourism and recreational activities), fisheries (e.g. commercial and recreational sources), sonar and seismic exploration (e.g. oil and gas exploration, Navy/ Military activity) (Richardson et al. 1995, Cato 2010, Wilcock et al. 2014). All these activities contribute significant levels of noise to the marine ambient environment (Hildebrand 2009, Cato 2010). Anthropogenic noise may result from activities that intentionally produce sound such as the use of air guns, sonar activity or acoustic deterrent devices such as pingers (Nowacek et al. 2007, Cato et al. 2013, Harcourt et al. 2014). It may also be produced by an unintentional byproduct of activities such as underwater construction, coastal development and shipping. The latter has been implicated as the main contributor of anthropogenic noise to the world's oceans (National Research Council 2005). In recent decades, many concerns have been raised about the effects of increasing levels of anthropogenic noise and their impact on baleen whale communication (National Research Council 2003, Nowacek et al. 2007, Weilgart 2007, Hildebrand 2009, Cato 2010).

Unlike toothed whales (odontocete), baleen whales (mysticete) do not echolocate but rather produce low frequency vocalisations that are essential for primary communication (Ketten 1992). Exposure of baleen whales to increased noise from anthropogenic activities may have negative effects, most of which are not well understood. Reported effects include (1) threshold shifts (temporary or permanent changes in an animal's ability to hear), (2) acoustic masking (inhibiting communication between individuals), (3) behavioural disturbance (behavioural responses to sound) and (4) displacement from critical habitat (Noad et al. 2004, Nowacek et al. 2007, Clark et al. 2009, Cato 2010, Hatch et al. 2012). Assessing whether the effects of noise have long-term impacts on baleen whales is difficult, and most work has focused on short-term visual and acoustic experiments (Clark et al. 2009, Wilcock et al. 2014).

The responses of several species of baleen whale to anthropogenic sounds have been varied with some sounds resulting in consistent responses across species while others have shown variability in response even within species. For example, North Atlantic right whales

(*Eubalaena glacialis*), blue whales (*Balaenoptera musculus*) and fin whales (*B. physalus*) compensate for loud ship noise by modifying their calls (McDonald et al. 2009, Parks et al. 2011, Castellote et al. 2012, Melcon et al. 2012, Parks et al. 2012). In contrast, North Atlantic right whales have shown no response to ship noise during playback experiments (Nowacek et al. 2004), while yet other right whales exposed to ship noise showed increased levels of stress hormones (glucocorticoids) (Rolland et al. 2012). In some situations whales have responded to anthropogenic noise that was distant from them. For example, playback experiments of drilling and dredging activity stimulated a variety of behavioural responses from bowhead whales (*Balaena mysticetus*), whereby some whales moved away in response to sounds with similar noise levels to drilling or dredging several kilometers away (Richardson et al. 1985, Richardson et al. 1990). Blue whales have also shown to call consistently more during social encounters and feeding in response to elevated ambient noise from seismic activities (Di Iorio & Clark 2009). While humpback whales (*Megaptera novaeangliae*) reduced calls in response to acoustic remote sensing activity approximately 200 km away (Risch et al. 2012).

The recovering East Australian humpback whale population (*Megaptera novaeangliae*) (Stock E1, Group V, currently recovering at 10.9% per annum (95% CI 10.5-11.3%) (Noad et al. 2010, Gales et al. 2011)) is exposed to a variety of different anthropogenic activities as they travel from their high latitude feeding grounds to their low latitude breeding grounds (Chittleborough 1965). Anthropogenic activities that humpback whales may encounter within this migratory corridor include shipping, tourism activities (whale watching), underwater construction, oil and gas exploration and fisheries.

Construction of the Sydney desalination plant began in 2008 (El Saliby et al. 2009), and as part of construction a marine platform was positioned directly within the humpback whale migratory corridor. Northerly migrating humpback whales travelling through the area were exposed to a variety of underwater construction activities close to or underneath the marine platform. These included drilling, dredging, diver activity, loose rock clearance, riser construction, spoil collection, and underwater tunnel (inlet/outlet) construction (Evans 2011).

This study aimed to assess the effects of this underwater construction on northward migrating humpback whales off Sydney, Australia. The construction of the Sydney desalination plant provided a unique opportunity to compare migratory humpback whale behaviour on days with and without construction. In addition, spatial data collected five-years later in the same location and using the same methods offers a unique comparative study of whale movements post construction. This study provides one of the first published studies of migrating humpback whale movements in response to underwater construction within a known migratory corridor.

10.0 Methods

10.1. Study Site

The study was conducted at Cape Solander in Botany Bay National Park, Sydney Australia (34° 01'S, 151° 14'E) (Figure 1). The location provided a unique opportunity to observe the behaviour of humpback whales as they pass through the area on their northward migration.

10.2. Desalination platform

A self elevating platform with cluster drill and drill rig was located 250 metres from the coastline, south of Cape Solander, off Tabbagai Point, Kurnell (Evans 2011). The platform was within sight of the observation platform at Cape Solander. Barges, tugs, support vessels and a helicopter assisted with underwater construction activities, which only occurred during favourable weather (Evans 2011).

10.3. Data Collection

Data were collected between 24 May and 31 July 2008, which coincided with the peak of the northern migration (Nicholls et al. 2000, Vang 2002, Gulesserian et al. 2011) using the method described in Gulesserian et al. (2011). Initial observations were made using the naked eye and 7 x 50 magnitude binoculars. All data were collected using a Sokkisha SET4A theodolite (with a precision of ± 5 seconds of arc and 30x magnification), set up at 1.47 metres high. The theodolite was placed on the Cape Solander observation deck that stands 30 metres above sea level and was connected to a laptop running custom software *Cyclopes*© (Version 3.16 Eric Kneist, University of Newcastle, Australia). The theodolite simultaneously measured horizontal and vertical angles to a target that was measured from a known reference object, Cape Banks (the headland north of the field site).

At least two people constantly scanned to the south for approaching pods. A pod was defined as either a lone whale or a group of whales. Tracking of selected pods began as far south as possible to maximise the tracking time. All whales that passed through the study site were on their annual northern migration and therefore each observation was considered independent.

Once a pod was seen, a focal animal was chosen to track, distinguishable by the natural variation in markings and dorsal fin shape. Every surface event was recorded for that focal animal as well as any associated behaviour with every surfacing. This occurred from the moment the pod was first sighted until it left the study area (>4000m north of the theodolite) or visibility was hindered. Common causes of poor visibility included intense sunlight, fog and sudden onset of heavy rain. Once a pod moved out of the study site, the next southernmost pod was selected for tracking (if present). All vessels were monitored using a 15 minute scan of vessel activity (Martin & Bateson 1998).

Observations took place from dawn until dusk (subject to daylight, but usually 0630-1700 hours) dependent on weather conditions. Observations were restricted to no rain and Beaufort state of ≤ 3. Weather recordings were taken throughout the day including Beaufort, swell, cloud coverage and rain.

10.4. Underwater construction

Construction activity only occurred in favourable conditions as strong currents, wave refraction, and turbulence limited operating times (Evans 2011). As we did not know exactly what type of underwater construction activity occurred each day, construction activities were treated as one unit (days with 'construction' and days with 'no construction'). Days on which construction / no construction occurred was confirmed post-hoc via a personal communication with the engineering firm.

10.5. Data Extraction and Analysis

All behavioural information for the focal animal was recorded, including the exact time of each surfacing and activity (±0.5second) and this information was exported directly onto a laptop running *Cyclops©.* A surfacing event is referred to each time the focal animal was visible from the surface.

To be included in the analysis, the pod must have been tracked for a minimum of 15 minutes and displayed multiple (two or more) dives. To assess the impacts of underwater construction on whale behaviour, we compared whale movements between days of construction (2008), no construction (2008) and post construction (2013). We assumed all whales that passed through the area on construction days were within audible range of underwater construction activities. Post construction data were collected five years after the initial study in the same location using the same methodology and provided a comparison of whale movements through the area post construction (no construction or desalination platform present).

To test for differences among treatments, we used linear mixed-effects models with individual whales (focal follows) as the random effect to account for individual differences. These included course from north (degrees), absolute course change (degrees), dive duration (seconds), and speed ($m\ s^{-1}$). Directional data measured the bearing between consecutive surfacing events relative to the north bearing (course from north) and the change in turn angles between these events (absolute course change). Dive duration (downtime) measured the dive duration of time between surfacing events (seconds). This was calculated as the time between the last respiration before a dive and the first respiration after a dive. We found that after each dive, whales remained at the surface to respire a number of times. To avoid calculating sequential surfacing respirations after a dive, all surfacing events less than 120 seconds (<two minutes) were not included in the analysis. As all data collection was done in real time, it was possible to calculate speed as a factor of time (in seconds) relative to the distance travelled between consecutive sightings ($m\ s^{-1}$). The log of both dive duration and speed were included for analysis.

As we couldn't observe whale behaviour underwater, these four behavioural metrics were chosen on the basis of being observable through the methodology used in this study. If the alarm was to have any effect on an individual whale, we may expect a change in whale speed, which may differ to its speed prior to entering within the acoustic range of detectability. Similarly, if whales responded to the alarm we might also see changes in respiration, with whales surfacing more or less frequently or changes in directional movements with whales either turning rapidly toward the alarm or moving away from the area. Linear mixed effects models are used for data that are collected and placed within groups. The use of linear mixed-effects models allowed us to explore differences in individual whale behavioral responses (random effect) within each treatment (fixed effect). Whale behavioural responses were grouped based upon the tone they were exposure to.

A cosine and logistic transformation was applied to all circular (directional) data (course from north and absolute course change). Distance of whales to location of the platform was also calculated by subtracting each surface location from the platform location. For all statistical analyses, the null hypothesis was rejected if $p < 0.05$. All statistical analyses were performed using the nlme library in the statistical software package R (Pinheiro et al. 2014) (R Foundation for Statistical Computing).

11.0 Results

There were 146 focal follows that met the criterion of a minimum of 15 minutes and two complete dives collected over 422 hours of observations in 2008 (76 focal follows on days with construction and 70 focal follows on days without construction). Post construction 56 focal follows were collected in 2013. Whale movements around the location of the construction platform are shown for each treatment group in Figure 2 a, b and c.

There was only one variable that differed among treatments from all the comparisons. Whales dived for significantly longer in 2013 compared to both construction and no construction days in 2008 (Table 1 and Figure 3 a). The mean dive duration across both 2008 treatments was 1 min (construction days SD= 1.60 min, n=76 and no construction days SD=1.73 min, n= 70) while in 2013, dive duration was significantly longer at 1.50 min (SD= 2.35 min, n= 56). No other variable differed. There was no significant difference in speed across all treatments (Figure 3b). The mean speed of whales during days with construction was 1.93 m s^{-1} (SD= 0.94 m s^{-1}, n=76) or 6.9km/h (3.8 nm) during days with no construction days was 2.06 m s^{-1} (SD= 1.07 m s^{-1}, n= 70) or 7.42km/h (4.0 nm) and during post construction was 2.2 m s^{-1} (SD= 1.17 m s^{-1}, n= 56) or 7.9km/h (4.3 nm).

Whale direction and absolute course change did not differ across all treatments (see Table 1 and Figure 3 c and d). The distance of whales to the location of the platform location was also similar during days with construction and days without construction and slightly farther post construction, without the presence of the platform (Figure 3 e).

12.0 Discussion

Interactions between baleen whales and human activities are likely to increase as the extent and frequency of anthropogenic activities continue to grow (Wilcock et al. 2014). This is particularly pertinent to the East Australian population of humpback whales as the population continues to grow (Noad et al. 2010). There are mounting concerns in particular about the consequences of increases in noise levels on all marine mammals (Erbe 2012). This study assessed the movements of northward migrating humpback whales in response to underwater construction that occurred within the narrow migratory corridor off Sydney, Australia. Humpback whales showed no detectable response to underwater construction, at least in terms of the four response variables we tested. Whales did not differ in directional movement (course from north and absolute course change) or speed between days with and days without construction (2008) and post construction (2013).

We did find that dive duration in 2008 and 2013 were significantly different. This difference is difficult to explain but might be attributable to either (1) to the presence of the platform in 2008 (even on no construction days), (2) to inter-observer error (there were different observers in the two years), (3) physiologic differences- dive intervals may be related to buoyancy and fat reserves of individuals or (4) to variation in the strength of the East Australian Current in the different years (Cetina-Heredia et al. 2014). Of note, there was an month-long anomaly in June-July 2013 whereby the south-flowing EAC did not flow along the continental slope which may have assisted the northward migration of whales in that year (IMOS Ocean Current News 2014). These results provide one of the first assessments of northward migrating humpback whale responses to underwater construction within a known migratory corridor.

Similarities between humpback whale movements through the study site suggests either: (1) whales were tolerant of underwater construction, (2) whales continued travelling past construction activity because it occurred within the narrow migratory corridor (Buck & Tyack 2000) or (3) responses occurred further south than the actual construction site, i.e. were not detected by the observer as they had already occurred beyond the scope of visibility. The latter is supported by reports from elsewhere that whales can detect activity at considerable distance. For example, Richardson *et al.* (1990) found feeding bowhead whales responded to drilling and dredging activity with received noise levels around 110 dB re.1 µPa audible at a distance of 3-11km away in the Canadian Beaufort Sea. Responses were variable among individuals, with some bowhead whales tolerant of drilling and dredging activity within 4-10km while others were not (Richardson et al. 1990). Assuming similar hearing capacity (Ketten 1992, Ketten 1997), it is likely that the migrating humpback whales within our study acoustically detected the underwater construction prior to entering the study site. However it is unknown if whales that might be less tolerant of noise moved offshore once encountering dredging and drilling noise. The average number of individuals (individual counts) passing through the study site was similar between days with underwater construction and days without. Richardson *et al.* (1990) also acknowledged that responses to drilling and dredging activities might be different for migrating bowhead whales.

Additionally, migration might be a key explanatory factor; for example migrating humpback whales appear indifferent to whale alarms (Harcourt et al 2014; Pirotta Chapter One). The inherent urge to migrate north may explain the similarities in directional movements (course from north and absolute course change) and speed, despite underwater construction. Migratory humpback whales generally take a more direct path when migrating northward in comparison to their southward migration (Horton et al. 2011). This is particularly evident along the Australian east coast migratory corridor through areas like Sydney, and may explain why directional movements did not differ between treatments. Furthermore, low variability in speed may be in part due to the behaviour of northward migrating humpback whales, which travel at nearly twice the speed compared to southward migrating humpback whales. For example, southward migrating humpback whales of the same population leaving their breeding grounds had an overall lower mean swim speed (Noad and Cato 2007) than the northward migrating whales in our study. Southward migrating (non-singing) humpback whales travelled at a mean speed of 4.0km/h (Noad & Cato 2007) which was lower than the average swim speed across whale movements (7.3km/h). This may explain why we saw no change in speed in response to underwater construction as whales neither sped up nor slowed down during construction. Humpback whales may not have regarded the presence of underwater construction as an inhibiting factor to their movements north. This result may differ for southward migrating whale behaviour where the presence of young calves may make adult individuals more vigilant of underwater construction.

Northward migrating humpback whales along the east coast of Australia (like other baleen whales), may have become accustomed to a wide variety of anthropogenic noise (Cato 2010).

In addition to underwater construction, migrating humpback whales travelling through the study site are also exposed to shipping and recreational vessel activity. Further, natural contributors to the ambient environment include wind dependent noise (breaking waves) and biological contributors from snapping shrimp, fish and other cetaceans (Cato & McCauley 2002). Humpback whales from this population reportedly compensate for high levels of ambient noise along the east coast by switching between vocal and surface-generated communication (Dunlop et al. 2010). The presence of underwater noise generated from drilling and dredging activity may have masked or inhibited communication among individuals within the area. However, no *in situ* noise measurements were taken and noise levels generated from underwater construction are unknown. This was likely a result of construction deemed as critical infrastructure (under section 75C of the *Environmental Planning and Assessment Act, 1979*) and was fast tracked due to the looming drought in the State of New South Wales (NSW Government: Planning & Environment 2009). Approval of only a concept plan was sufficient for addressing environmental impacts, in comparison with a more detailed assessment usually required at a federal based level, such as an Environmental Impact Assessment (EIA) which may have required noise levels assessments (El Saliby et al. 2009, NSW Government: Planning & Environment 2009). Despite this, the fact that whales continued to pass through the study site suggests that the individuals we tracked were not measurably disturbed by the noise levels. It is possible that the persistence of underwater construction noise may have simply been yet another addition to the already noisy environment off the east coast of Australia.

This study provides one of the first assessments of interactions between northerly migrating humpback whales and underwater construction. Similarities between whale responses across all treatments suggests northward migrating humpback whales were relevantly tolerant of drilling and dredging activities within a narrow migratory corridor off Sydney. This study provides empirical evidence that underwater construction of this scale does not have detectable effects on northward migrating humpback whales off the east coast of Australia.

13.0 Acknowledgments

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Chapter Two: Tables and Figures

2. Table legends

1.3. Table 1: Results from linear mixed effects models for all four-response variables.

Whales dived (seconds) for significantly longer in 2013 compared to both construction and no construction days in 2008. There was no significant difference between speed (m s^{-1}) and absolute course change (degrees) between construction and no construction days. In comparison, course from north (degrees) is significantly less than that of construction. This table details the treatment type, parameter estimate, standard error, t-value and p-value for each response variable.

Course from north (degrees) (random effects (SD); intercept: 0.8172211, residual: 1.524223), absolute course change (degrees) (random effects (SD); intercept: 0.5127058, residual: 2.63162), dive duration (seconds) (random effects (SD); intercept: 0.2751925, residual: 0.3118314) and speed (m s^{-1}) (random effects (SD); intercept: 0.2636285, residual: 0.3220035).

1.4. Table 1

Response variable	Treatment	Parameter estimate (value)	Standard Error	t-value	p-value
Dive duration (seconds)	Construction	5.487870	0.03621620	151.53081	0.0000
	No construction	-0.004417	0.05249599	-0.08415	0.9330
	Post construction	0.177077	0.05456352	3.24534	0.0014
Speed (m s^{-1})	Construction	-0.0333373	0.03530950	-0.944146	0.3454
	No construction	-0.0084187	0.05119345	-0.164449	0.8695
	Post construction	-0.0508728	0.05341618	-0.952386	0.3421
Course from north (degrees)	Construction	3.729691	0.1258045	29.646726	0.0000
	No construction	-0.403011	0.1826269	-2.206746	0.0285
	Post construction	-0.256229	0.1867868	-1.371773	0.1717
Absolute course change (degrees)	Construction	3.677455	0.1520329	24.188547	0.0000
	No construction	-0.186571	0.2210095	-0.844174	0.3996
	Post construction	0.280888	0.2193793	1.280378	0.2019

Chapter Two: Figure Legends

Figure 1: Location of study site, Cape Solander, Sydney, Australia.

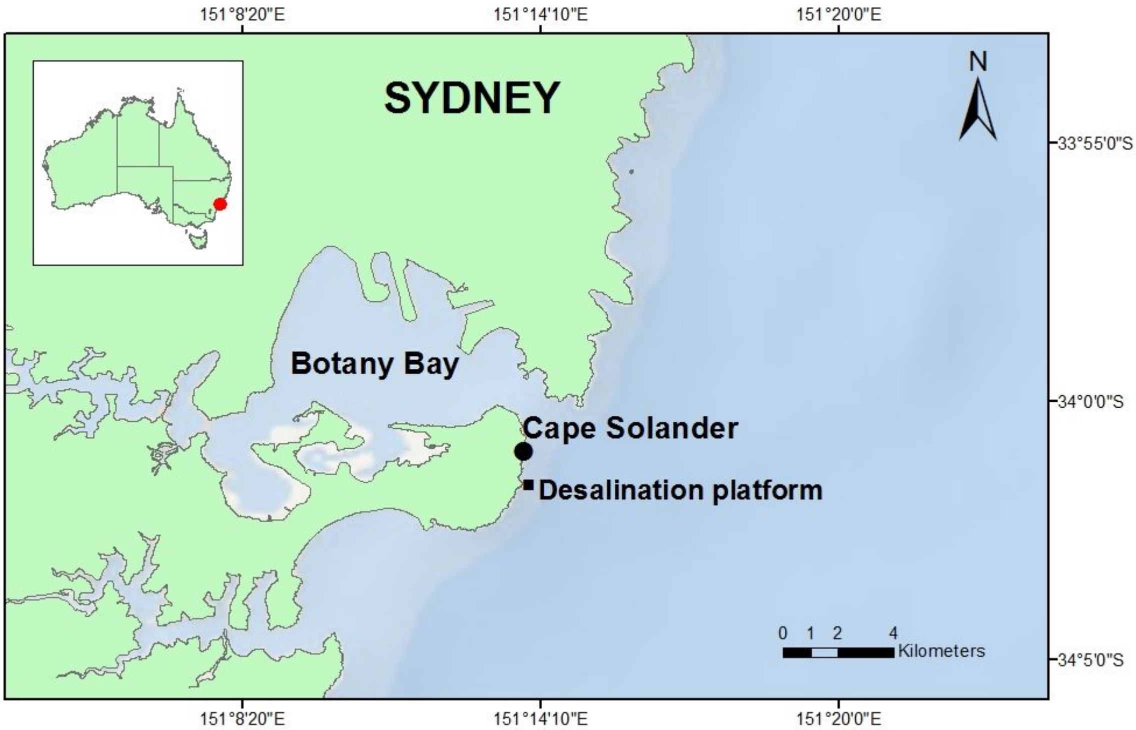
Figure 2: All focal follows collected on days with a) construction (2008), b) days without construction (2008) and c) post construction (2013). Desalination platform location indicated by the black square (250 metres from shore). Each dot represents a single whale surfacing along individual focal follows. The triangle represents the location of the theodolite.

Figure 3: Results from directional data: a) course from north (degrees), b) absolute course change (degrees) and non-directional data: c) dive duration (min) subset of all surfaces >=120 seconds, d) speed (m s^{-1}) and e) average distance to platform (km).

Figure 4: Directional data focal follow distribution a) course from north and b) absolute course change for each individual focal follow.

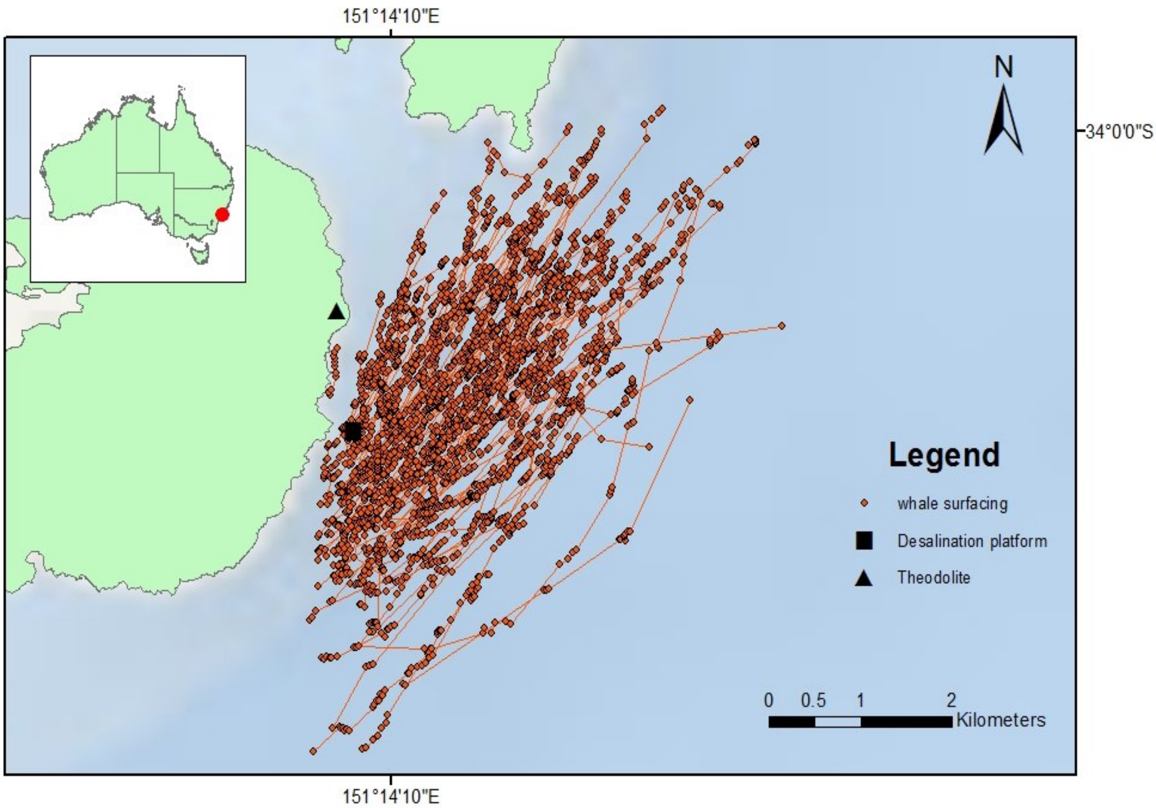
Chapter Two: Figures

1.7. Figure 1



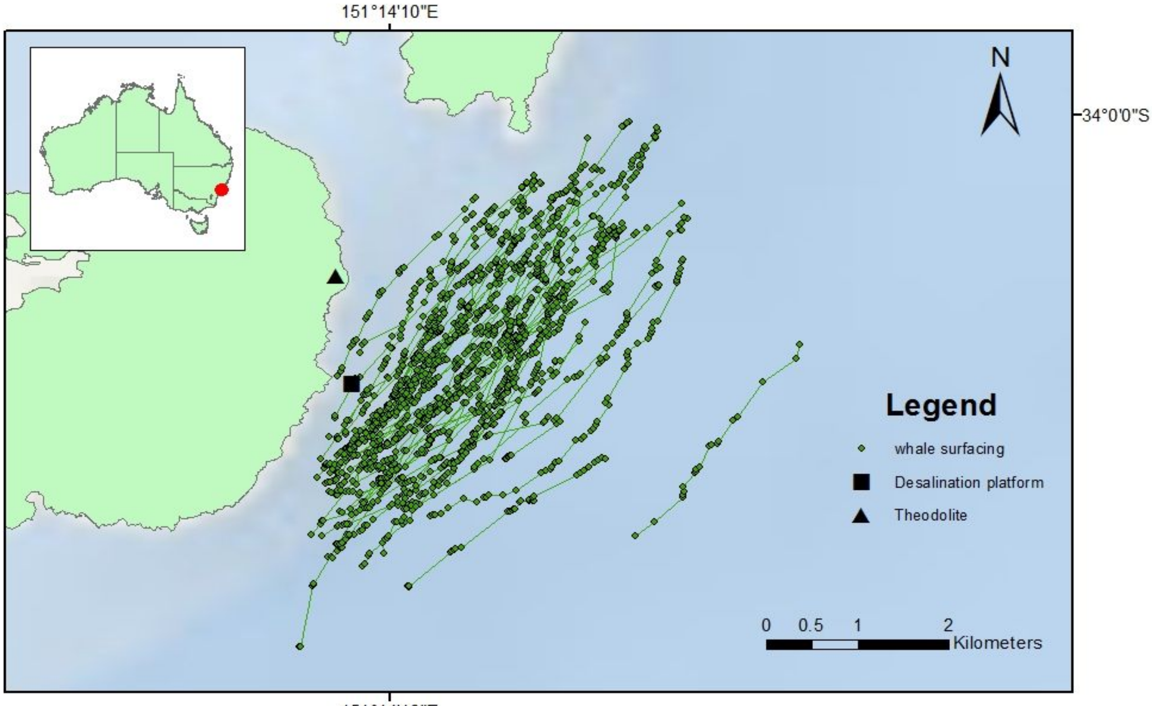
1.8. Figure 2 a

a

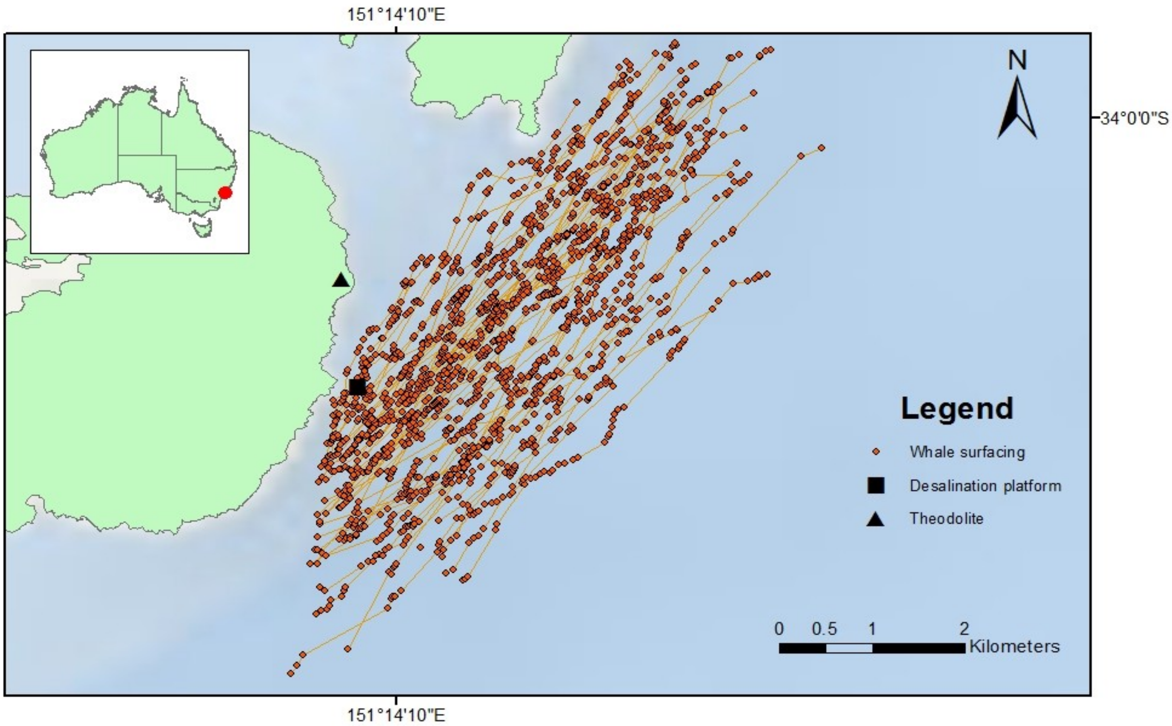


1.9. Figure 2 b and c

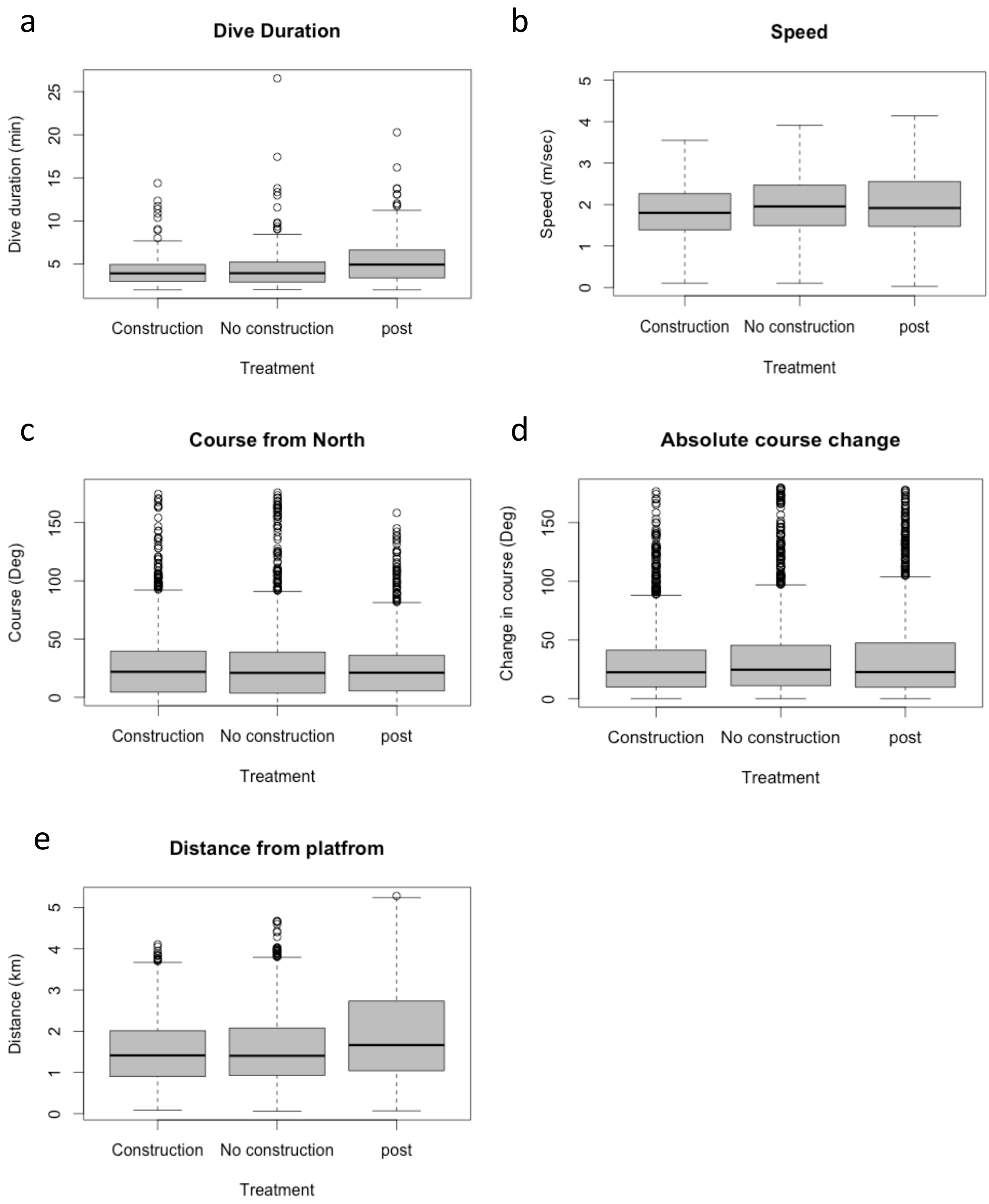
b



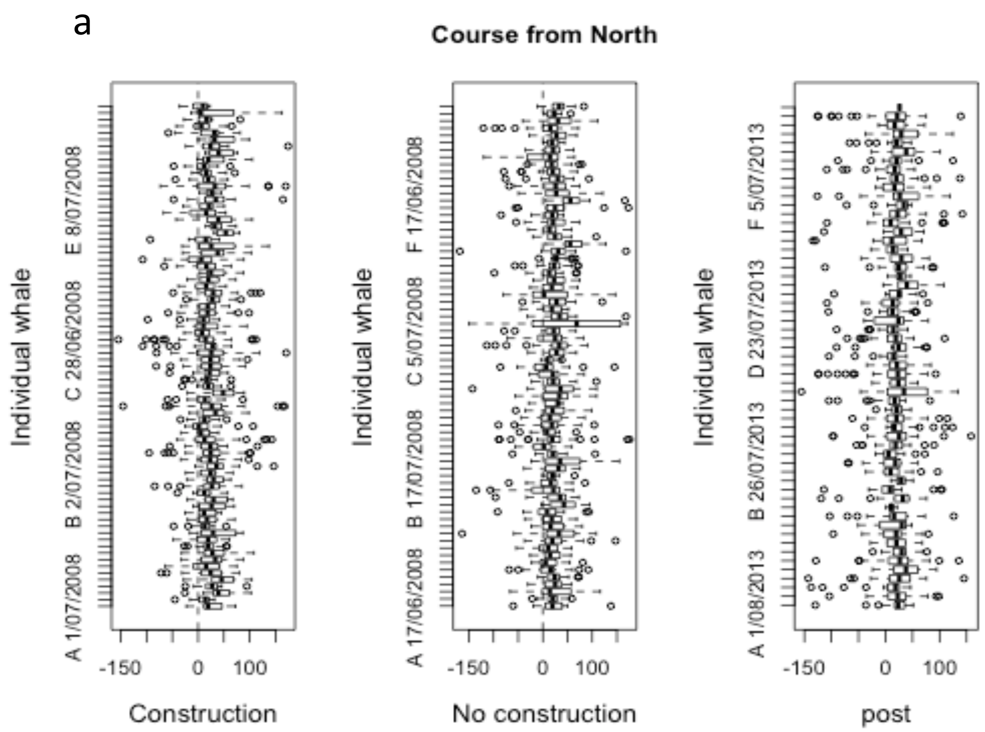
c



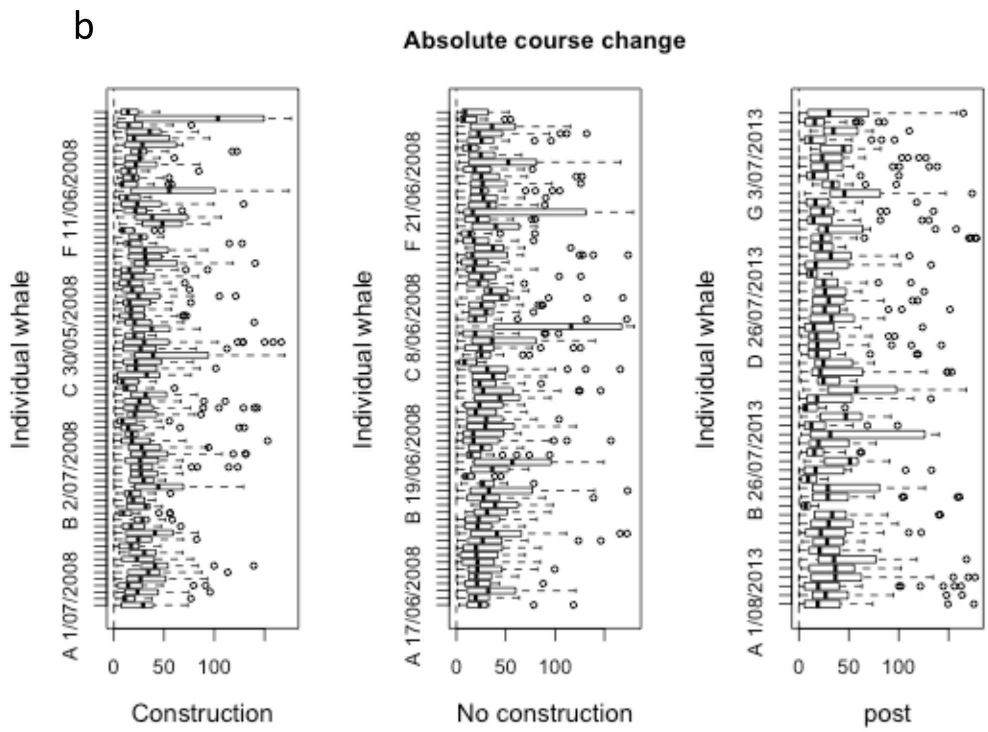
1.10. Figure 3


a
Dive Duration
Dive duration (min)
5
10
15
20
25
Construction
No construction
post
Treatment
b
Speed
Speed (m/sec)
0
1
2
3
4
5
Construction
No construction
post
Treatment
c
Course from North
Course (Deg)
0
50
100
150
Construction
No construction
post
Treatment
d
Absolute course change
Change in course (Deg)
0
50
100
150
Construction
No construction
post
Treatment
e
Distance from platfrom
Distance (km)
0
1
2
3
4
5
Construction
No construction
post
Treatment

1.11. Figure 4



a
Course from North
Individual whale
A 1/07/2008
B 2/07/2008
C 28/06/2008
E 8/07/2008
-150
0
100
Construction
A 17/06/2008
B 17/07/2008
C 5/07/2008
F 17/06/2008
No construction
A 1/08/2013
B 26/07/2013
D 23/07/2013
F 5/07/2013
post



b
Absolute course change
Individual whale
A 1/07/2008
B 2/07/2008
C 30/05/2008
F 11/06/2008
0
50
100
Construction
A 17/06/2008
B 19/06/2008
C 8/06/2008
F 21/06/2008
No construction
A 1/08/2013
B 26/07/2013
D 26/07/2013
G 3/07/2013
post

Discussion

Southward migrating humpback whale passing Sydney with dolphin escorts.

14.0 Discussion

This thesis investigated the responses of migrating humpback whales in relation to two anthropogenic activities within the migratory corridor off Sydney, Australia: (1) fisheries interactions and (2) underwater construction. Results provided in the first chapter of this thesis expand on current whale alarm research by examining the use of a more complex acoustic tone to try and prevent whale entanglement in fishing gear. In addition, the second chapter presents one of the first studies to have measurable responses of migrating humpback whale behaviour to small-scale underwater construction.

The east coast migrating humpback whale population provides a unique opportunity annually to observe northward whale movements off Sydney, Australia. Through shore-based methods involving the use of a theodolite, we were able to conduct non-invasive observations and spatial data collection of humpback whale movements throughout the study area. Observations were only collected on the northward migration. Therefore, each observation/focal follow was independent as all whales were heading in a northward direction.

Results from chapter one found that whales did not respond to either acoustic treatment, with no difference between directional movement (course from north and absolute course change), speed or dive duration. Whales may have been alerted to the tone but took no action to avoid the area or regarded the acoustic tones as merely another anthropogenic noise contributing to the ambient environment. These results suggest that particular acoustics, such as the lobster/crab pot single fishing gear scenario we tested fitted with an alarm, are ineffective in preventing whale entanglement in fishing gear. This highlights the need for future research in order to determine what type of acoustics may be effective in generating an avoidance response in whale behaviour. Future research may involve looking beyond acoustics or using a combination of acoustic and visual based alerting methods. Once this is determined, trialing the use of new technology will aid in the prevention of whale entanglement in other types of fishing gear responsible for whale mortalities.

Chapter two investigated the responses of migrating humpback whales to underwater construction within a migratory corridor off Sydney, Australia. Overall migrating humpback whales had similar directional movements (course from north and absolute course change) and speed across days with, without and post construction. However whales had significantly longer dive durations post construction in comparison with days with construction. We discussed possible explanations based on either (1) the presence of the platform in 2008 (even on no construction days), (2) to inter-observer differences, (3) physiologic differences- dive intervals may be related to buoyancy and fat reserves of individuals or (4) to variation in the strength of the East Australian Current in the different years. Overall, these findings suggest migrating humpback whales are not affected by short-term underwater construction within a known migratory corridor at the scale within this study.

Limitations

Collectively, these two studies provide insight into short-term migrating humpback whale behavioural responses towards two anthropogenic activities, however both studies were subject to limitations. Common limitations between both studies included:

1. Sampling only northward migrating humpback whales: responses towards both activities may have been different for southward migrating humpback whales. For example, pod compositions in northward migrating humpback whales are more likely to comprise of adult individuals and groups. In comparison, southward humpback whales are more likely to contain a mixture of cow calf pairs. Parental care in southward humpback whales may cause whales to respond differently to both activities.
2. Shore based observations: both studies only involved large scale tracking in comparison to fine scale tracking. As a result, this methodology may not have detected fine scale underwater activity in the vicinity of the acoustic alarm and underwater construction.

Limitations between studies include:

1. Testing only one type of whale alarm fishing gear type scenario (chapter one). Results from this study only apply to lobster/crab pot fishing gear. Testing needs to be applied in other types of fishing gear that are responsible for whale entanglement where the use of multiple alarms are used in one line e.g. long lines, shark nets.
2. Testing only two types of acoustic tones (chapter one). Further research should include a variety of complex tones in attempts to alter whale movements away from the sound source.

3. Study site location (chapter 2): Responses to underwater construction noise levels may have been audible much further away than is visible from the study site. As a result of the study site position, the beginning of whale observations occurred close to or nearly directly within the vicinity of the marine platform. Therefore whale responses to underwater construction were only gathered from individuals that passed within an area with noise compared with individuals that may have responded to noise levels and chose not to move into the study site.

In conclusion, this thesis provides insights into responses by northward migrating humpback whales in the presence of two types of anthropogenic activities. Given the likelihood that some anthropogenic activities within the ocean are likely to increase (Richardson et al. 1995, Wilcock et al. 2014), alongside the recovery of some baleen whale populations (Carroll et al. 2011, Gales et al. 2011), this thesis provides timely evidence of baleen whale responses to anthropogenic activities. While it appears that underwater construction within a known migratory corridor had no effect upon migrating humpback whales (at least in the four response variable we tested), results from this thesis suggests there is a strong need for further research into the use of acoustic alarm technology in attempts to prevent whale entanglement in fishing gear. Future efforts to reduce entanglement, as demonstrated within chapter one, should be at the forefront of baleen whale conservation biology research. Whale entanglement is a serious global problem and is a main cause of whale mortality in some baleen whale populations (Bradford et al. 2009, Cassoff et al. 2011). The results of this thesis will help inform future fisheries mitigation research trying to prevent baleen whale entanglement, not only within Australian waters, but hopefully around the world.

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Supplementary Material

Humpback whale entangled in fishing gear off Peru.

15.0 Guidelines for ESR Authors

The Editors consider for publication:

- Research Articles (target: ~6000 words)
- Reviews, state-of-the-art evaluations of important current research areas
- Notes, brief reports of important new information deserving priority publication (target: <3000 words)
- Comments, critical, fair assessments of published works and Reply Comments, replies to Comments (target: ~2000 words); for details on Comments/Reply Comments click here)
- As I See It, important, personal views on hot topics (brief and fair)
- Theme Sections, integrated expert analyses highlighting an important current research area or problem (contact the Editorial Office for details)

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General: include manuscript page and line numbers, use MS Word format, aim for <5 MB in size

Title: aim for a length of <100 characters

Running page head: provide a shortened title (3 to 6 words)

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In-line citation style: no comma before the year, 'et al.' in regular font, citations separated by comma, '&' instead of 'and' for citations with 2 authors. Examples: "... previously been shown (West & Amrose 1992, Smith et al. 2000, Johnston 2002)", "... as shown by West & Amrose (1992)..."

Archiving of data: authors are asked to deposit supporting molecular and phylogenetic data in a public database such as GenBank, TreeBASE or Dryad, and to give the accession number in the manuscript. The data must be accessible on the date of publication.

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Literature cited: see examples below. IR citation styles are available at www.endnote.com/support/enstyles.asp or download.

Periodicals: Penston MJ, Millar CP, Davies IM (2008) Reduced *Lepeophtheirus salmonis* larval abundance in a sea loch on the west coast of Scotland between 2002 and 2006. Dis Aquat Org 81:109-117

Books: Van der Schalie H (1973) Effects of temperature on growth and reproduction of aquatic snails. University of Michigan Library, Ann Arbor, MI

Book series: Hanski I (2005) The shrinking world: ecological consequences of habitat loss. In: Kinne O (ed) Excellence in ecology, Book 14. International Ecology Institute, Oldendorf/ Luhe

Chapters/papers from books, proceedings, etc.: West TL, Amrose WG (1992) Abiotic and biotic effects on population dynamics of oligohaline benthic invertebrates. In: Colombo G, Ferrari I, Ceccherelli VU, Rossi R (eds) Marine eutrophication and population dynamics. Proc 25th Eur Mar Biol Symp. Olsen & Olsen, Fredensborg, p 189–194 Barnes RSK (1991) Reproduction, life histories and dispersal. In: Barnes RSK, Mann KH (eds) Fundamentals of aquatic ecology. Blackwell Science, Oxford, p 145–171

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Electronic supplements: material unsuitable for inclusion within the article (overlong tables, mathematical derivations, video clips, computer code, etc.) may be published on the Inter-Research web-site as an electronic supplement.

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16.0 Ethics approval

MACQUARIE UNIVERSITY

ANIMAL RESEARCH AUTHORITY (ARA)

AEC Reference No.: 2012/016 - 3 **Date of Expiry:** 31 May 2014

Full Approval Duration: 01 June 2012 to 31 May 2014 (24 Months)

This ARA remains in force until the Date of Expiry (unless suspended, cancelled or surrendered) **and will only be renewed upon receipt of a satisfactory Progress Report before expiry.**

Principal Investigator:
Professor Rob Harcourt
Dept of Environment and Geography
Macquarie University
NSW 2109
0421 780 434

Associate Investigators:
Dave Slip 0432 886 278
Vic Peddemors 0411 537 268
Geoff Ross 0411 110 882
Vanessa Pirotta 0439 480 600

Other people participating
Andre Steckenreuter 0410 862 189

In case of emergency, please contact:
the Principal Investigator / Associate Investigator named above
or Animal Welfare Officer 9850 7758 / 0439 497 383

The above-named are authorised by MACQUARIE UNIVERSITY ANIMAL ETHICS COMMITTEE to conduct the following research:

Title of the project: **An empirical assessment of whale alarms and avoidance, or not, by migrating humpback whales**

Type of animal research: **7 – Research: Environmental Study**

Aims of project: **To test the efficiency of low-frequency alarms as a short-term deterrent of large cetacean to nets and gear.**

Surgical Procedures category: **1 - Observation involving minor interference**

All procedures must be performed as per the AEC-approved protocol, unless stated otherwise by the AEC and/or AWO.

Maximum numbers approved (for the Full Approval Duration):

Species	Strain	Sex	Weight	Age	Total	Supplier/ Source
44F – Whales and Dolphins	*Megaptera Novaeangliae*	N/A	N/A	N/A	~150/annum	wild
				TOTAL	~150/annum	

Location of research:

Location	*Full street address*
Botany Bay Kamay National Park	Coastal waters, Sydney, Australia

Amendments approved by the AEC since initial approval:

1. Addition of Vanessa Pirotta as Associate investigator (Exec approved 16 April 2013, ratified by AEC 18 April 2013).

Conditions of Approval: **N/A**

Being animal research carried out in accordance with the Code of Practice for a recognised research purpose and in connection with animals (other than exempt animals) that have been obtained from the holder of an animal suppliers licence.

Professor Mark Connor (Chair, Animal Ethics Committee) **Approval Date:** 16 May 2013

Adapted from Form C (issued under part IV of the Animal Research Act, 1985)