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Reduced Detection of Indo-Pacific Bottlenose Dolphins (*Tursiops aduncus*) in an Inner Harbour Channel During Pile Driving Activities

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Abstract

There is limited information on the impacts of anthropogenic noise on dolphin behaviour, making assessment and mitigation of impacts from anthropogenic noises difficult. As the use of echolocation and other vocalizations are of vital importance for cetaceans, it is important to better understand the potential impact of anthropogenic acoustic disturbance. The small Indo-Pacific bottlenose dolphin (*Tursiops aduncus*) community that inhabits the Fremantle Inner Harbour regularly travels through an area where impact and vibratory pile driving occurred during wharf upgrading. The overall aim of this study was to measure the noise energy created by pile driving associated with wharf construction activities in the Fremantle Inner Harbour and to determine whether the reduced detection of dolphins within the vicinity of the wharf was associated with pile driving activities. Measuring noise was accomplished with noise loggers and a hand-held digital acoustic recorder, under water, allowing identification of signals produced by impact and vibratory pile drivers and calculating the energy of recorded noise. Dolphin detections in the Inner Harbour were conducted by examination of high-definition video recordings. The association of pile driving and dolphin detections was assessed using Generalized Estimation Equations (GEEs), using observations before and during pile driving. The final model indicated that there was a difference in detections between the two treatments, with more dolphin detections observed when there was no pile driving activity taking place (mean = 0.26 ± 0.03 SE) than during pile driving (mean = 0.18 ± 0.04 SE). Knowledge generated by this study on the impact of noise on bottlenose dolphins improves the scientific basis for managing anthropogenic noise and reducing impacts on marine mammals.

Key Words: pile driving, underwater noise, port construction, cetacean detection, impacts, Indo-Pacific bottlenose dolphin, *Tursiops aduncus*

Introduction

The current literature regarding potential impacts of man-made noise on dolphins and other marine life is limited (Popper & Hastings, 2009; André et al., 2011). However, sounds are of vital importance for odontocetes as they use echolocation and other vocalizations to find prey (Madsen et al., 2006), socialize (Gedamke & Scholik-Schlomer, 2011), communicate, and perceive the environment (David, 2006). Dolphins may be susceptible to undesirable effects from anthropogenic noise, including sound generated by industrial construction and maintenance activities such as pile driving. Pile driving is a mechanical process in which a large hammer mounted on a crane is used to drive piles into the soil or seabed. As a noise source, pile driving can vary in intensity, frequency bandwidth, and acoustic energy. Pile driving noise has been reported to have the potential to mask sounds that dolphins rely on for navigation, group cohesion, capturing prey, and avoiding predators (Erbe, 2013). Pile driving noise also has the potential to cause behavioural changes in animals; or if high enough in energy, it has the potential to cause hearing damage or physiological injury (Richardson et al., 1995; Southall et al., 2007; Bailey et al., 2010; Erbe, 2013). The level effects depend upon the signal characteristics and intensity, the environment through which the signal transmits, the sensitivity of the animals receiving the signals, and the distance of the receiving animal from the source. Masking of dolphin communication, for example, such as whistles produced for group cohesion (Janik & Slater, 1998; Erbe, 2013) or sounds associated with feeding activities (Janik, 2000), can occur if the noise is within the same frequency band and high enough in energy to "drown" out the sounds produced by dolphins.

While the potential for these effects has been well described, few studies present empirical evidence of these effects, and the existing few are variable in their results. For example, Würsig et al. (2000) reported no changes in numbers of Indo-Pacific humpback dolphins (*Sousa chinensis*) observed in an area of pile driving activity but did report increased swim speeds during pile driving. Dähne et al. (2013) documented avoidance responses by harbour porpoises (*Phocoena phocoena*) during pile driving activity associated with construction of an offshore wind farm. Three harbour porpoises in captivity also showed avoidance reactions to the start of pile driving noise in a study in Denmark (Lucke et al., 2011). Tougaard et al. (2009) stated a significant rise in intervals between echolocation events after harbour porpoises were subjected to noise from pile driving. Brandt et al. (2011) reported decreased acoustic activity (and by inference, either vocalization and/or abundance) of harbour porpoises with decreasing range from pile driving activity associated with the construction of offshore wind farms. Another study conducted on a harbour porpoise in captivity exposed to playbacks of recorded pile driving sounds reported increased respiration rate and surfacing behaviours (Kastelein et al., 2013). While there are limited studies on dolphins, research on other marine mammals have also shown high variability, including results ranging from limited to significant responses such as avoidance of areas where there is pile driving noise present (e.g., grey whales [*Eschrichtius robustus*]; Southall et al., 2007).

The overall aim of this study was to measure the noise energy created by pile driving during wharf constructions in the Fremantle Inner Harbour, located in the southwest region of Western Australia, to determine the number of dolphin detections associated with pile driving activity within 0.11 km^2 in its direct vicinity. The Fremantle Inner Harbour plays an important role in the regional and national economy, particularly in the export of livestock and motor vehicle imports (Fremantle Ports, 2011). In 2010, wharf construction was undertaken in the Inner Harbour to increase its capacity to accommodate larger ships and enable a greater number of ships to be filled to their full transport capacity. The construction equipment required to deepen the port area in the Inner Harbour included impact and vibratory pile drivers. During impact pile driving, piles were driven into the soil by weights that are lifted and hammered on the piles, whereas vibratory pile drivers enabled piles to penetrate the ground by applying vibrations to the top of the pile. The underwater sound characteristics of impact and vibratory piling are different as is their transmission through water (Duncan et al., 2010). The distance that their acoustic energy transmits underwater depends upon the frequency and energy of the source, bathymetric characteristics, and sediment type among other factors (Schulkin & Marsh, 1962; David, 2006; Bailey et al., 2010; André et al., 2011; Lucke et al., 2011).

The Inner Harbour is located at the entrance of the Swan-Canning Estuary, which is an important part of the natural heritage of Perth, both for visitors and residents (Finn, 2005; Moiler, 2008; Lo, 2009). The Inner Harbour is frequently used by Indo-Pacific bottlenose dolphins (*Tursiops aduncus*) that are resident to the area (Chabanne et al., 2012). Bottlenose dolphins using the Inner Harbour include over 20 individuals from a community of around 100 that are resident to an adjacent embayment known as Cockburn Sound (Finn, 2005; Lo, 2009), and around 25 individuals making up the entire community of dolphins resident to the Swan-Canning Estuary (Moiler, 2008; Chabanne et al., 2012). The deaths of six bottlenose dolphins from the Swan-Canning Estuary in 2009 highlighted the vulnerability of the population and the high risk of local extinction (Stephens et al., 2014). The species *T. aduncus* is currently classified as "data deficient" by the International Union for Conservation of Nature (2015), and, therefore, assessing potential impacts of anthropogenic activities on this species is required to manage and mitigate potential effects.

The specific objectives of this study were (1) to measure underwater sound energy of pile driving at various ranges from the source; and (2) to determine the presence of bottlenose dolphins within the vicinity of vibratory and impact pile driving activity by using a high-definition video camera. The outcomes of this research have applications for reducing the uncertainty in current knowledge on potential impacts of pile driving activity on Indo-Pacific bottlenose dolphins.

Methods

Study Area

The Fremantle Inner Harbour (32.04° S, 115.75° E) is located in Fremantle, Western Australia, 23 km from the capital city of Perth (Figure 1). The

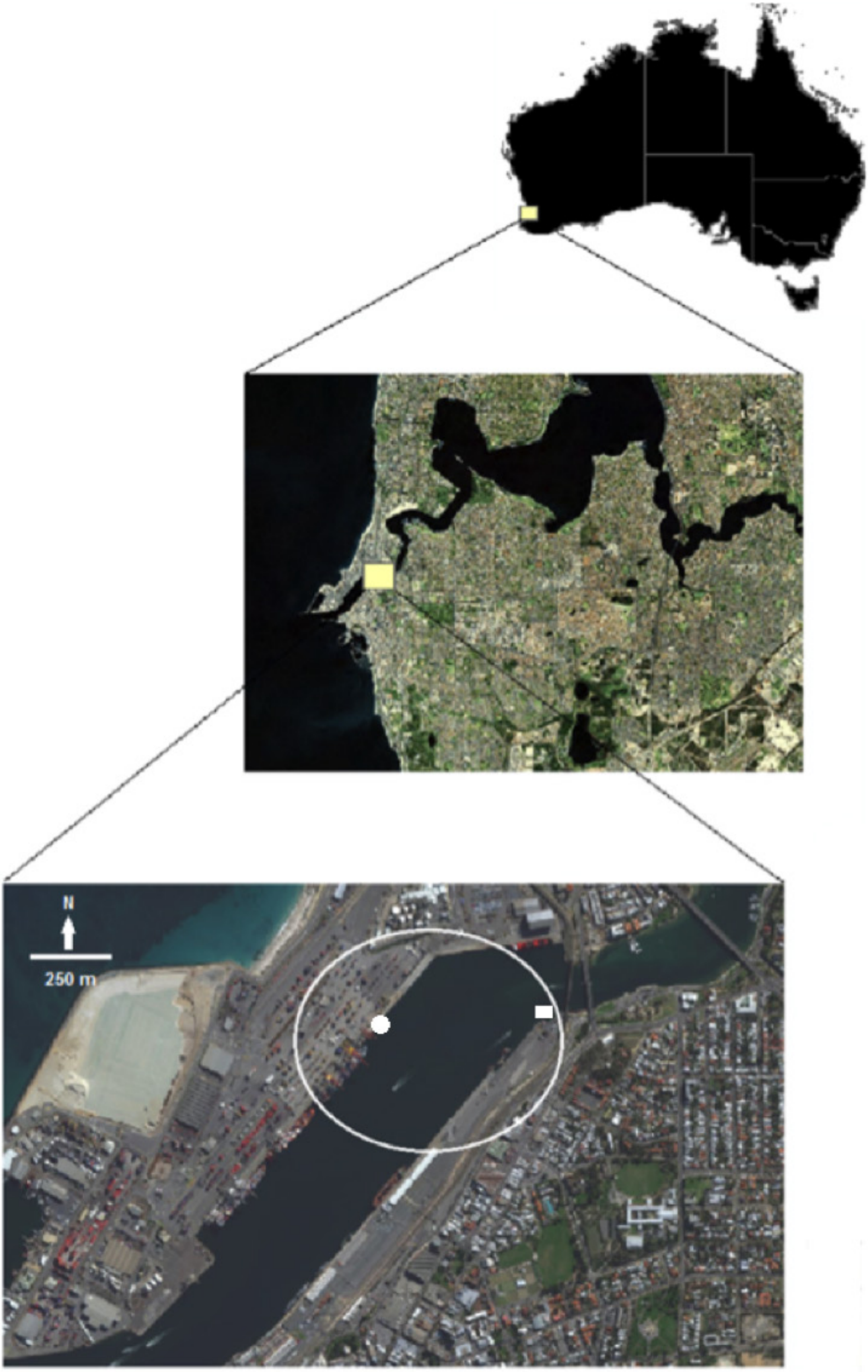

Figure 1. Study area within the Inner Harbour of the Port of Fremantle, Western Australia. The circle delineates the general study site, the white rectangle indicates where the camera was positioned, and the solid circle indicates the location where pile driving occurred (adapted from Paiva et al., 2015).

region is characterized by a Mediterranean climate, which is relatively dry with cool, wet winters (Bureau of Meteorology, 2011). The harbour area connects the Indian Ocean with the Swan-Canning Estuary, which is the habitat for a range of animals, including Indo-Pacific bottlenose dolphins, water birds, fish such as mulloway (*Argyrosomus japonicas*; Parsons et al., 2010) and whiting, and invertebrate species.

The Inner Harbour is 2,500 m long and 450 m wide (Chabanne et al., 2012). The entrance channel is approximately 13.4 m in depth, whereas the Inner Harbour is about 14.7 m in depth, varying due to siltation. Dredging did not occur during the period of this study. The noise spectrum of the Inner Harbour is dominated by anthropogenic sources such as machinery noise, vessel traffic, and noise from trains and automobiles passing over adjacent bridges (Salgado-Kent et al., 2012).

Data Acquisition

Acoustic Recordings—Noise measurements of pile driving activity within the Inner Harbour were obtained in two ways: (1) by a digital hand-held acoustic recorder with the hydrophone deployed from a 6-m outboard vessel on a single day (7 May 2010) when pile driving was occurring for measurement of energy levels, and (2) a fixed noise logger deployed on the seabed at approximately 14.7 m depth over the ~4-mo period. For hand-held recordings, in order to obtain a noise-level decay curve with distance from the source, 2-min-long measurements were made at different distances from the pile drivers along two azimuths during the same piling event which occurred over a period of approximately 1 h. Several minutes of recording at each distance allowed for tens of strikes to be recorded so that the variability could be estimated. Distances from the source were roughly doubled at each recording, starting with the closest possible approach of approximately 40 m.

The gear used for acoustic measurements included a Reson Hydrophone (TC4033, SN 4703110) set at 4-m depth with a sensitivity from 10 Hz to 80 kHz of -202 dB re V/µPa; a Reson VP1000 preamplifier with 0 to 32 dB gain in 6 dB steps; and a SoundDevices 744T digital recorder set at 48 kHz sample rate, 24 bit dynamic range, and with gain settings from -6 to 18 dB adjustable in 0.1 dB steps. The system gain was calibrated with white noise of known spectral level. The system was deemed to have a flat frequency response over 10 Hz to the upper frequency limit of 24 kHz, and the instrumental stated gains were confirmed through calibration. Range was measured in the field using Bushnell laser range finding binoculars targeted on the respective source piles (i.e., locations where piles were being driven). For each recording, sections with pile driving signals were identified by examining the waveforms and by listening to the sound file to verify that piling was the source.

For the fixed noise logger placed on the seabed, CMST-DSTO sea noise loggers (developed by the Centre for Marine Science and Technology, Curtin University, Perth, Western Australia) were deployed within the Inner Harbour. Two deployments of the same unit were carried out. The first was 1 April to 2 July 2010 and the second was late 26 July to 20 August 2010. The hydrophone was positioned external to the housing unit, which was weighted and entered the housing via a bulkhead connector. The hydrophone signal was high-pass filtered with a cut-off frequency of 8 Hz, which reduced the contribution of very low frequency noise of high level present in sea noise so as to increase the system's dynamic range. An anti-aliasing filter of 5 and 2.8 kHz and total gain of 40 and 0/20 dB (two channels) for the first and second deployments, respectively, were then applied to the signal before it was fed to an analogue-to-digital converter. The underwater noise was sampled according to a pre-programmed sampling schedule of 5-min recordings every 15 min. The sample rate for noise level measures was 12 kHz for the first deployment and 6 kHz for the second deployment. The change in sample rate was a result of a strategic decision to improve battery longevity (hence, recording time) with the addition of two channels set with different gains (to ensure that saturation did not occur).

The electronic part of the logger receive channel was calibrated according to the process described by Salgado-Kent et al. (2012). The signals produced by impact and vibratory pile drivers were identified in Power Spectrum Density (PSD) plots of recorded noise, and the times and dates of samples with pile driving noise documents.

Video Camera Recordings—Activity of marine mammals, other animals, and vessels within the vicinity of pile driving activity was recorded with a digital video camera (high-definition Sony HDR-XR520V), powered by two car batteries. The camera was placed in a watertight box and set on a purpose-built, 3-m tower on the opposite side of the channel from where pile driving activity was occurring. The camera was set up facing the sector of water where wharf construction activities were occurring (Figure 2). Servicing, including replacement of batteries and memory cards, was done twice per week.

The range, bearing, and decline in detections of bottlenose dolphins with range have been previously calculated for this camera set-up (Paiva et al., 2015). The field of view covered an area

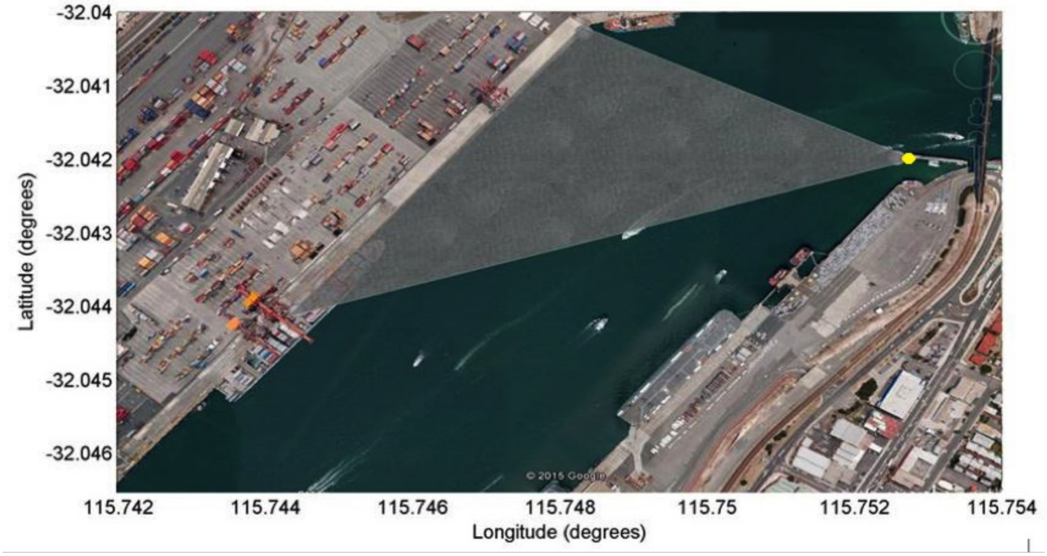

Figure 2. The field of view (grey triangle) covered by the video camera (yellow solid circle) within the Inner Harbour of the Port of Fremantle, Western Australia; adapted from Paiva et al. (2015).

of about 114,000 m², and the most distant detection range was 463.3 m. Bottlenose dolphins were detected between 245° and 299° with reference to geographical north. The camera was set to automatically obtain continual footage of the area during daylight from 0600 to 1800 h. Video recordings were inspected at a speed 1.75 times faster than normal, using *VLC© Media Player*, Version 2.1.5, to search for bottlenose dolphins. This playback speed has been shown to be the most effective when examining video for confirmation of bottlenose dolphins at the water's surface in a channel (Paiva et al., 2015) as it optimizes the efficiency of data review but does not lead to significant dolphin misdetections.

A selection of 42 d of video between April and August 2010 were inspected. These included video with no rain and no areas fully covered by haze, and in which acoustic and video recordings were made simultaneously. Even though effort was made to select the days that were at the same period of the tidal cycle to control for tidal cycle effects, the days selected were chosen aiming to have enough sample size of each treatment and type of pile driving. Vibratory pile driving was present on 16 April 2010, 8 May 2010, 18 May 2010, 24 July 2010, and 2 August 2010; impact pile driving was present on 28 April 2010, 29 April 2010, 5 May 2010, 6 May 2010, 15 May 2010, 17 May 2010, 26 May 2010, 27 May 2010, 15 July 2010, 16 July 2010, 17 July 2010, and 29 July 2010; and both vibratory and impact pile drivers were present on 7 May 2010, 21 July 2010, 22 July 2010, 23 July 2010, 26 July 2010, 28 July 2010, 30 July 2010, and 31 July 2010.

Dolphin detections within the field of view of the camera were recorded as a *transit event*. A transit event consisted of an individual or a group of bottlenose dolphins passing through the field of view of the camera, from the time the dolphin first surfaced to the time it left the field of view. Some bottlenose dolphins transit through the channel (i.e., they head out to sea or upriver and do not stay in the Inner Harbour), while others remain in the Inner Harbour for periods of time (and, thus, are likely to be "re-captured" as another transit event later on) as they move around the Inner Harbour. The duration of transit events ranged from < 1 s (when only one surfacing was detected) to 1.5 min. There were no events in which a group circled within the view of the camera. All events consisted of animals entering from one side of the field of view and exiting from the other side. Correcting for detection probabilities with range was not relevant here as the aim of the present study was to obtain detections of transit events within the study area as relative indices (counts of transit events in 5-min periods) rather than to estimate abundance and distribution of bottlenose dolphins within the study area.

Data were inspected by multiple observers who were trained and under the direct supervision of one main observer to ensure consistency in data processing. Also, all observers were required to follow strict guidelines described in a detail in an *Observation Methods Manual*. Environmental conditions were recorded at the time of each transit event and included cloud cover (recorded in eighths), light level (0 = no light; 1 = dusk and dawn; 2 = daylight), haziness level (0 = no haze; 1 = front; 2 = middle; 3 = far – related to the far side of the harbour), amount of glare (0 to 4; 0 being "no glare" and 4 being "severe glare"), sea state according to Beaufort scale (1 to 12), tidal height (in m), presence or absence of rain, and percentage of the surface of the lens covered by droplets or sunspots. Conditions were assessed by the observer reviewing the video data with the exception of tidal height, which was determined using tide tables for the Inner Harbour. Beaufort condition levels greater than 5 (associated with increased wind conditions) are likely to affect detectability when using cameras, as well as when observers perform the work in the field. This is mostly due to the state of the water rather than movement of the camera from the wind. Treatments were classified as (1) N (no pile driving), (2) I (impact pile driver), (3) V (vibratory pile driver), and (4) B (both types of pile drivers) based on an auditory and visual review of spectrograms of logger recordings corresponding to the video time periods. For example, if there was impact pile driving present even for a portion of the 5-min sampled period (of the pre-programmed underwater noise logger schedule of 5-min recordings every 15 min), the period was allocated an "I" as the treatment.

Data Analysis

Hand-Held Digital Acoustic Recordings—Recordings were viewed, and an amplitude threshold from the SoundDevices 744T digital recorder (with the output scaled from -1 to 1 Volts) was obtained, as well as the minimum time spacing between pulses. An algorithm was run in order to locate the impulsive signals by detecting the first peak of each signal that was above the selected threshold amplitude (high enough to be above background noise but low enough to include all pile driving signals) and which was at a time interval greater or equal to the minimum time between pulses.

Consecutive pile driving pulses were extracted by selecting a time interval around the pulse such that a small section of time before the peak (0.4 s) and the decaying signal after the main peak (0.4 s) were included. Signal amplitude in volts was transformed into pressure units using the preamplifier and SoundDevices 744T digital recorder gain settings, hydrophone sensitivity, and 20 dB gain of the normalized voltage conversion process in .wav file recording. The resulting noise levels were reported in average mean square pressure (MSP) for vibratory and sound exposure level (SEL) for impact pile driving at various ranges from the pile driving activity.

Underwater Noise Loggers—Data were processed using a *Matlab© R2011b* (The MathWorks, Inc., Natick, MA, USA) toolbox named "CHORUS" (Characterisation of Recorded Underwater Sound), developed by the Centre of Marine Science and Technology (Curtin University, Perth, Western Australia). The toolbox sorted each of the 5-min continuous noise recordings by their recording time, removed spikes from the sea noise signal in each recording, and then calculated the PSD of recorded noise. The de-spiking procedure removed spikes of non-acoustical origin from ambient noise and filled short gaps appearing in the waveform using an autoregressive interpolation algorithm, which allowed preserving spectral characteristics of the sea noise recorded.

The PSD was calculated for each 20-s fragment of all individual continuous recordings and then was converted into the PSD of the received acoustic pressure measured in dB re 1 $\mu Pa^2/Hz$ using the calibration procedure described above. The resulting PSD calculated for all recordings made within every 5-d period of observation were combined and stored in *Matlab© R2011b* data files.

Video Camera Recordings—First, a subset containing only the 5-min acoustic recording sample periods (previously scheduled in the noise logger recordings) was created to allow investigation on counts of transit events corresponding to 5-min recordings. The association of the number of transit events detected with pile driving activity was assessed using Generalized Estimation Equations (GEEs) with a log-link function (for Poisson distributed count data). GEEs are used to account for residual autocorrelation in longitudinal data (Zeger & Liang, 1986; Thall & Stephen, 1990; Zorn, 2001; Zuur et al., 2009; Staley, 2013). GEEs are robust in providing consistent estimates of mean parameters even when the correlation structure is mis-specified. This is because GEE uses a *sandwich estimator* to estimate the average response over the population.

Models using a CReSS-GEE (Scott-Hayward et al., 2013a) framework, which was used to estimate smooth terms in the models using *R* (R Core Team, 2013), were fitted through *RStudio*, Version 0.98.501 (© 2009-2013 RStudio, Inc.), using the following packages: *MRSea* (Scott-Hayward et al., 2013b), *doBy* (Højsgaard et al., 2013), *stringr* (Wickham, 2012), and *geepack* (Yan, 2002; Yan & Fine, 2004; Højsgaard et al., 2006). In order to build the model, a summary of the independent variables was produced to identify and remove variable levels with less than 20 samples per covariate level (Harrell, 2001) or insufficient spread over the study period. Furthermore, observations made during poor weather conditions associated with reduced dolphin detectability were removed. Because of the large influence that high values of glare and Beaufort have had at this site in previous research (Paiva et al., 2015), their influence was removed by subsetting the dataset so that it only included observations made during glare of 0 or 1 and Beaufort conditions less than 3. Level of cloud cover in this subset was not evenly distributed over time (with few occasions of high levels of cloud cover early in the study) and, therefore, was not used in the model.

Model predictors included *Treatment* and *Ten-Day Time Block*. Treatment had two levels defined as *pile driving* and *no pile driving*. Observations associated with no pile driving consisted only of those made during days with no pile driving, or during periods before pile driving commenced on those days in which pile driving occurred. Also, vibratory and impact pile driving were grouped together due to the relatively small sample size of vibratory piling after subsetting the data. Ten-Day Time Block was included as a vector of integers ranging from 1 to 11, numbered as sequential Ten-Day Time Blocks during the study period. Four blocks were removed for analyses to allow sufficient observations for an interaction term between Ten-Day Time Block and Treatment to be included in the model. The effect of *Tide* was also tested in the model. The function "runSALSA1D" in the *MRSea package* was used to select smoothness of the covariates Tide and Ten-Day Time Block. The resulting model selection indicated a linear fit as being the best for Ten-Day Time Block and a smoothed fit as the best for Tide.

Regression analyses were run in order to investigate the presence of highly correlated variables. Variance Inflation Factors (VIFs) were calculated, and those of < 3 were considered not to be collinear (Zuur et al., 2009). The VIF for Tide was above 3, so this variable was removed.

To select the clusters to use for the model (ID), we checked the decline in correlation over time by plotting the autocorrelation of the model residuals by ID. We found that during a *Day* (a sequential value beginning on Day 1 and ending on the last day of sampling), the correlation during all days (clusters) declined to approximately zero. Therefore, Day was used as the ID. The order of time for the correlation structure was defined by a vector of time of day, expressed in decimal hours. An AR-1 correlation structure was initially selected for this study since it is used for datasets in which there is a time order (Zuur et al., 2009). While AR-1 was selected as the initial preferred correlation structure, the GEEs were run with multiple correlation structures (e.g., independence, unstructured, and exchangeable) to ensure that consistent estimates and standard errors (SE) were obtained (as suggested by Staley, 2013), and the best fit was selected using Quasi-likelihood information criterion (QIC; Pan, 2001). The models with all structures fit except for *unstructured* (which did not converge) had consistent QIC values. While AR-1 was selected for the final model, results were compared for all model structures to ensure consistency.

Initially, a full model was fitted, containing all variables (Treatment and Ten-Day Time Block) and their interaction. The biological justification for including this interaction relies on the fact that the combination of these factors could affect dolphin transit event detections. For example, animals could habituate to the noise over time. Explanatory terms of no significance (beginning with the largest p values) were eliminated one by one, refitting the model each time, and checking and validating the model by checking observed vs fitted values to assess model fit as well as plotting fitted values vs scaled Pearson's residuals to assess the mean-variance relationship. QICu was used for final model selection (Pan, 2001; Hardin & Hilbe, 2002; Cui, 2007; Hudecová & Pešta, 2013). The model that reduced the QICu by > 2 values with the fewest terms was selected. ANOVA was used to cross check models to test whether large changes in QICu corresponded with significant differences in model fit when a term was removed. All significant terms were retained in the final model.

Results

Sound Pressure Levels of Pile Drivers

A total of 13 recordings were made with the handheld recorder within the Inner Harbour on 7 May 2010, and all were suitable for analysis (they had no recording artefacts in them). Locations of the recordings ranged from 42 to 295 m from the pile driving source (Table 1). Included in the recordings were ambient sound (reported in Salgado-Kent et al., 2012), impact pile driving, and vibratory pile driving measurements. Noise levels in Inner Harbour during periods when pile driving was not occurring were typically between 110 and 140 dB re 1 µPa^2 (MSP; Salgado-Kent et al., 2012).

It is important to consider that different pile strikes are not consistent in the amount of noise they generate. The SEL of impact pile driving was 158 dB re 1 µPa^2·s at 54 m from the pile driver, with an expected SEL of approximately 161 dB re 1 µPa^2·s at the wharf perimeter (Figure 3). Noise levels from the vibratory pile driver were 163 dB re 1 µPa at the closest range of 42 m from the

Table 1. Measurements made on 7 May 2010. Hydrophone depth = 4 m; pre-amp hi-pass filter – 5 Hz.

Description	Recording	Range during recording (Min-max in m)
Impact pile driving	1	280
	2	143-154
	3	72-81
	4	54-60
	5	122-133
	6	272-295
	7	56-62
	8	118-121
Impact & vibratory piling	9	234-255 impact, 218-225 vibratory
Vibratory piling	10	42-44
	11	45-46
	12	118
Ambient noise (including machinery noise and passing power boat)	13	227-257

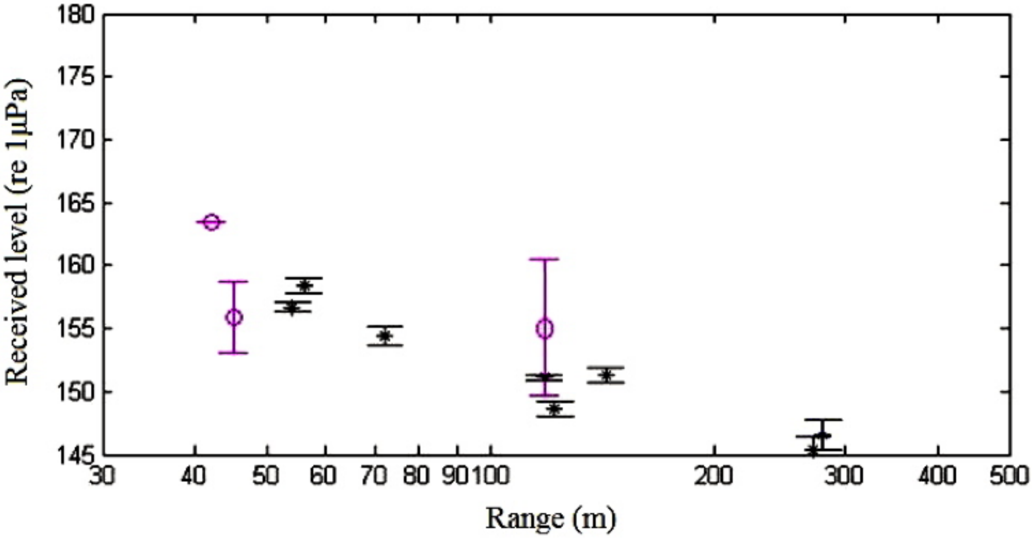

Figure 3. Measured sound pressure levels of pile driving, including (1) impact pile driving in SEL in units of dB re 1 µPa^2 · s (black stars); and (2) vibratory pile driving in mean square pressure (MSP) levels in units of dB re 1 µPa (magenta circles); the error bars are standard deviations of pile driving signals measured at that range.

pile driver located at the perimeter of the wharf. Measured noise levels of the vibratory pile driver did not exceed 163 dB re 1 µPa. Based on the measurements taken, noise levels at the source could be expected to be as high as 175 dB re 1 µPa.

Association of Pile Driving with Dolphin Detection

A total of 42 d were sampled over a period of 3.5 mo in 2010, including 9 d in April, 12 d in May, 3 d in June, 17 d in July, and 1 d in August. Pile driving, either impact, vibratory, or both, was detected on 25 of the 42 d in noise logger recordings, including 3 d in April, 9 d in May, 12 d in

Table 2. Significant terms, Wald statistics from which the *p* values (Pr [> (W)]) were calculated to test the significance of the effects, and *p* values (Pr [> (W)]) associated with the best Generalized Estimating Equation (GEE) submodel for predicting transit event detections. Asterisks denote significance level: *** = ≤ 0.001.

Coefficients	Estimate	Std error	Wald	Pr (> |W|)	Sig. levels
Intercept	0.120	0.485	0.06	0.8054	
Treatment – Vibratory & impact piling	-1.628	0.480	11.50	0.0004	***
Block	-0.195	0.043	12.41	0.0006	***
Treatment*Block	0.162	0.049	10.88	0.0009	***

July, and 1 d in August. A total of 493.4 h of video recordings were examined.

After subsetting the data for modelling and running these data through the model selection process, the model with the best fit (the final model) was found to be with day given by, the sample time over the study period in the autocorrelation structure given by, and as the intercept (Table 2). The scale parameter was 1.27.

The final model indicated that Treatment had a large effect on the number of transit events detected (Table 2; Figures 4 & 5). The reduced dataset did not allow sufficient samples to test vibratory pile driving on its own, so Treatment represents impact and vibratory pile driving combined. Utilizing the reduced dataset used to construct the model (which excluded observations associated with glare and Beaufort conditions above sea level 2, and includes observations before and during pile driving but not after), more dolphin transit events were detected when there was no pile driving activity taking place (mean = 0.26 ± 0.03 SE) than during pile driving (mean = 0.18 ± 0.04 SE). The Ten-Day Time Block during the study also had a significant effect on number of transit events detected, with a decrease in numbers over time (Figures 4 & 6). The interaction between Treatment and Time Block indicated that the difference in treatments was more pronounced during the earlier period of the study when there were more bottlenose dolphins in the area (Figure 4).

Discussion

In this study, the number of dolphin transit events detected was significantly greater when no pile driving activity occurred than when there was pile driving activity. There was also a decline in detections over the study period (possible a seasonal effect), but this was not associated with an increase in pile driving activity. Rather, pile driving activity occurred throughout the study period.

While this study does not directly measure noise levels received at locations where bottlenose dolphins were detected, the measurements indicated that for the bottlenose dolphins to pass through the narrow channel of ~450 m wide during pile driving, they would have been exposed to levels above 140 dB (regardless of whether impact or vibratory pile driving was occurring). The noise levels during pile driving were higher than when pile driving activity did not occur (see ambient noise measurements reported in Salgado-Kent et al., 2012). Overall noise spectra of the Inner Harbour are dominated by broadband sounds common to a busy port, with noise levels typically between 110 and 140 dB re 1 µPa (MSP) when pile driving is not occurring (Salgado-Kent et al., 2012). While bottlenose dolphins using the Inner Harbour are regularly exposed to a relatively noisy environment, noise from pile driving elevated the level within the range in which behavioural responses have been observed in other studies (Southall et al., 2007). In this regard, our observations of reduced dolphin transit events during pile driving agrees with other published studies. The above-mentioned levels for pile driving in this study, however, are not within the range expected to result in physiological damage to dolphins (Southall et al., 2007).

While impact pile driving often is associated with greater acoustic energy at close range than continuous noise such as vibratory pile driving, the piles being driven to strengthen the existing wharf during this study appeared to be behind existing structures at the channel's edge. Resulting attenuation or reflection of some of the acoustic energy from impact piling may explain the lower than expected received levels. It is worth noting here that several studies have reported reduced behavioural responses after implementation of an air bubble curtain used to attenuate sounds produced by pile driving, which would partially absorb, reflect, and refract the sound (Lucke et al., 2011). Also, the application of a soft start (Leopold & Camphuysen, 2008) combined with bubble curtains (Würsig et al., 2000; MacGillivray & Racca, 2005) has been suggested for mitigation, although the applicability of the soft start merits further

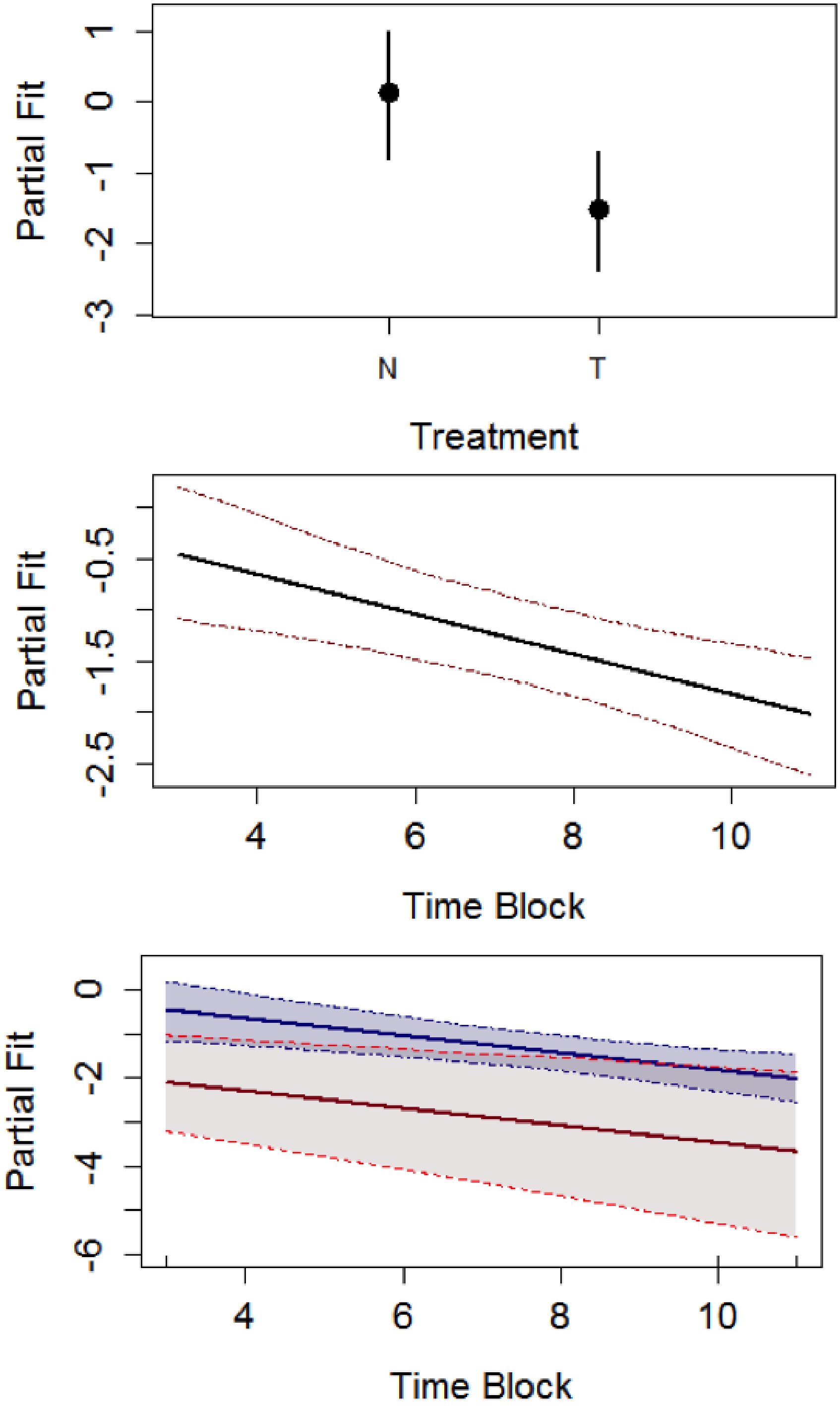

Figure 4. Partial residual plots produced from the best Generalized Estimating Equation (GEE) submodel for predicting dolphin transit event detections; partial residual plots are shown for Treatment (T = pile driving or N = no pile driving; upper panel), Ten-Day Time Block (middle panel), and their interaction (lower red line represents pile driving and upper blue line represents no pile driving; lower panel). Error bars and shaded areas represent 95% confidence intervals.

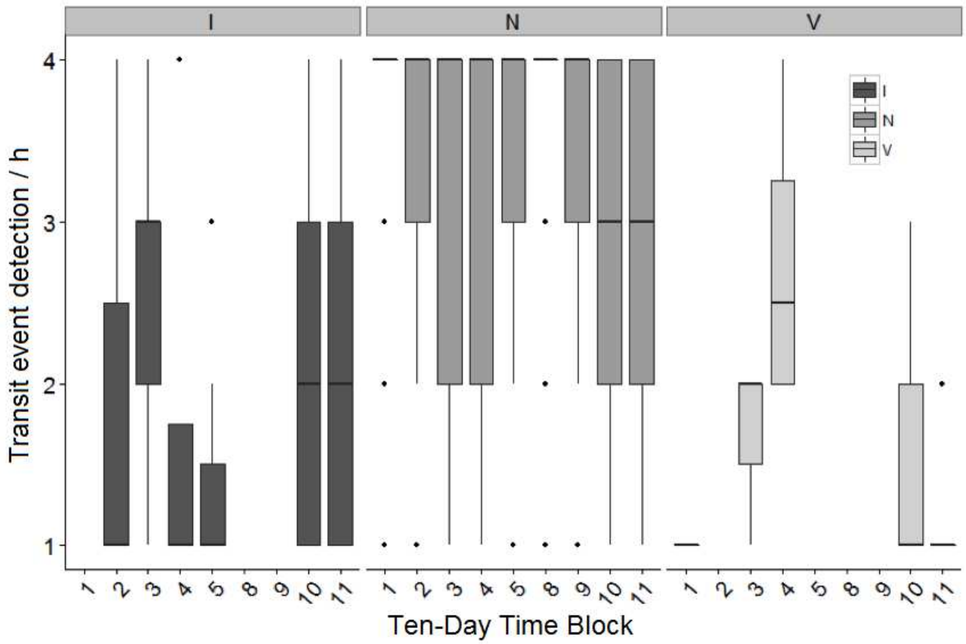

Figure 5. Box plots showing the distribution (means and quartiles) of the dolphin transit event detections h¹ over each Ten-Day Time Block for the three different pile driving treatments: I = impact pile driving, N = no pile driving, and V = vibratory pile driving.

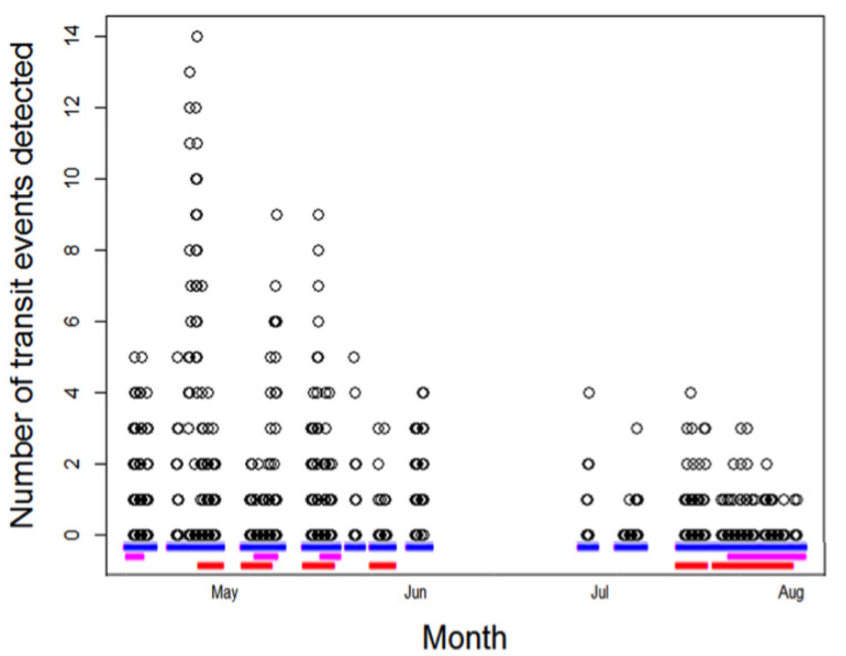

Figure 6. Dolphin transit events detected per day in association with pile driving treatments over the survey period (treatments recorded at the time are indicated by the bottom red line near the x-axis = impact pile driving, top blue line near the x-axis = no pile driving, and middle magenta line near the x-axis = vibratory pile driving; using data from full dataset).

investigation (Gedamke & Scholik-Schlomer, 2011).

While this study detected fewer transit events in the vicinity of pile driving, the spatial and temporal extent of the behavioural change could not be determined beyond the area within the camera's field of view. The camera used for observation had a fixed field of view covering an area of 0.11 km^2. Also, this study focused on observations during 5-min acoustic recordings (when pile driving noise could verify pile driving activity) before and during pile driving activity, and did not quantify the time required for a return to activity levels after cessation of pile driving. While pile driving for many days for several hours per day could cause temporary changes in or disruption of dolphin behaviour (Bailey et al., 2010) due to the large fluctuations in transit events within days and across days, this study could not distinguish between a natural seasonal decrease in detections from an effect of pile driving activity over time. Moreover, there has been some evidence (although not conclusive) that bottlenose dolphins may occupy the area more often or for longer periods during the season corresponding with the first 2 mo of this study (Moiler, 2008).

It is important to emphasize that avoidance reactions due to disturbance are subjected to various factors and, therefore, are complex to analyze (Bejder et al., 2009). A decrease in detections could be related to displacement of bottlenose dolphins (in the sense of reducing the abundance of bottlenose dolphins that occur within the Inner Harbour) so as to alter their behaviour in the harbour (e.g., reduce their residence time within the Inner Harbour). A decline in detections could also be associated with decreased milling activity or increased dive times. Masking, for example, could reduce the conspecifics' ability to communicate, and, thus, a decrease in surface socializing could occur. Alternatively, pile driving could affect the abundance and distribution of prey or the ability of bottlenose dolphins to detect their prey, thus changing the behaviour of dolphins that use the area to forage.

Many bottlenose dolphins from the Cockburn Sound and Swan-Canning Estuary are known to pass on a near-daily basis through the channel to move between the estuary and adjacent coastal waters (Chabanne et al., 2012; Stephens et al., 2014). Bottlenose dolphins from these communities also are known to feed and engage in other activities (e.g., socializing and resting) regularly within the Inner Harbour (Moiler, 2008). Past observations in the area by the authors of the present study indicate that repeated transiting across the field of view of the camera would have likely been due to groups of bottlenose dolphins using the area as a hotspot for foraging. Milling while foraging and socializing between periods of foraging commonly occur over extended periods of time (an hour or several hours). In the presence of pile driving, bottlenose dolphins may have reduced their activities to transiting only for the purpose of travelling through the area to reach coastal waters from the estuary, or the estuary from coastal waters. The bottlenose dolphins also could have moved further upriver or downriver to forage and socialize during pile driving activity.

While the camera provided a relatively cost-effective method for detecting activity of bottlenose dolphins (Paiva et al., 2015), it could not provide information on the exact nature and spatial extent of behavioural changes detected. Advances in video camera techniques for monitoring bottlenose dolphins (among other species) is expected to attract further interest from industry and environmental management agencies since it is a less expensive, autonomous option for collecting long-term data, which is important for the management of marine mammals in their habitats. This method of data collection has been effective in providing insight into the effects of pile driving on detections. However, the method is limited in the more detailed behavioural information it can provide.

Finally, more studies on the impact of noise on marine systems, such as this one and those referred to in this study, improve the scientific basis for managing anthropogenic noise. Not only is there high variability in sensitivity and responses across species, but variation also exists within communities of the same species. While much more challenging to address, there continues to remain a large gap in our current knowledge on the long-term effects of industrial noise on marine mammals (Popper & Hastings, 2009) in conjunction with cumulative impacts from multiple noise sources and stressors (Southall et al., 2007).

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