

Responses of bottlenose dolphins and harbor porpoises to impact and vibration piling noise during harbor construction

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Abstract. The development of risk assessments for the exposure of protected populations to noise from coastal construction is constrained by uncertainty over the nature and extent of marine mammal responses to man-made noise. Stakeholder concern often focuses on the potential for local displacement caused by impact piling, where piles are hammered into the seabed. To mitigate this threat, use of vibration piling, where piles are shaken into place with a vibratory hammer, is often encouraged due to presumed impact reduction. However, data on comparative responses of cetaceans to these different noise sources are lacking. We studied the responses of bottlenose dolphins and harbor porpoises to both impact and vibration pile driving noise during harbor construction works in northeast Scotland, using passive acoustic monitoring devices to record cetacean activity and noise recorders to measure and predict received noise levels. Local abundance and patterns of occurrence of bottlenose dolphins were also compared with a five-year baseline. The median peak-to-peak source level estimated for impact piling was 240 dB re 1 μPa (single-pulse sound exposure level [SEL] 198 dB re 1 $\mu\text{Pa}^2 \text{ s}$), and the r.m.s. source level for vibration piling was 192 dB re 1 μPa . Predicted received broadband SEL values 812 m from the piling site were markedly lower due to high propagation loss: 133.4 dB re 1 $\mu\text{Pa}^2 \text{ s}$ (impact) and 128.9 dB re 1 $\mu\text{Pa}^2 \text{ s}$ (vibration). Bottlenose dolphins and harbor porpoises were not excluded from sites in the vicinity of impact piling or vibration piling; nevertheless, some small effects were detected. Bottlenose dolphins spent a reduced period of time in the vicinity of construction works during both impact and vibration piling. The probability of occurrence of both cetacean species was also slightly less during periods of vibration piling. This work provides developers and managers with the first evidence of the comparative effects of vibration and impact piling on small cetaceans, enabling more informed risk assessments, policy frameworks, and mitigation plans. In particular, our results emphasize the need for better understanding of noise levels and behavioral responses to vibration piling before recommending its use to mitigate impact piling.

Key words: acoustic disturbance; anthropogenic noise; behavioral response; coastal development; environmental risk assessment; marine mammal conservation; marine protected area.

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INTRODUCTION

There is increasing awareness of the potential impacts of anthropogenic noise on marine mammals (Southall et al. 2007, Williams et al. 2015), requiring consideration within environmental assessments under many national and regional legislative frameworks (McCarthy 2004). However, efforts to develop policy frameworks and risk assessments for anthropogenic noise exposure are hampered by uncertainty over the spatio-temporal scales at which different noise sources may impact marine mammals (Nowacek et al. 2007, Ellison et al. 2012).

Pile driving during the construction of marine infrastructure (e.g., harbors, wind farms) can produce high levels of noise that may injure or disturb marine mammals (Bailey et al. 2010b, Brandt et al. 2011, Russell et al. 2016). Expert groups have developed noise exposure thresholds to provide an indication of the potential risk of injury from piling noise. However, uncertainty over behavioral responses to pulsed sources has constrained efforts to develop similar criteria for behavioral responses to impact piling noise (Southall et al. 2007). This can result in conservative estimates of behavioral displacement (Thompson et al. 2013b), requiring developers to modify project plans and mitigate potential risks. While precautionary measures minimize certain risks to protected marine mammal populations (Jefferson et al. 2009), they may delay or prevent infrastructure projects that could provide wider environmental benefits (Inger et al. 2009). In some cases, vibration piling has been encouraged as a quieter alternative to impact piling. The vibratory hammer uses pairs of rotating eccentric weights to apply oscillatory downward force on the pile, and is suitable for use in softer seabed types. However, uncertainty remains over the extent to which marine mammals may respond to these different noise sources. Similarly, some of the mitigation measures used to reduce source noise levels (see Wursig et al. 2000, Verfuss et al. 2016) could result in additional environmental costs, for example, through increased vessel traffic and carbon outputs. Cumulative impact assessments are therefore needed to underpin decisions that balance the environmental benefits and costs of different management and mitigation options.

With increasing pressure to develop coastal infrastructure (Bulleri and Chapman 2010), these assessments require an understanding of how the scale of behavioral responses to different noise sources varies across species and contexts (Southall et al. 2007, Ellison et al. 2012, Williams et al. 2015). This evidence base has increased through recent studies on the extent of displacement around pile driving (Brandt et al. 2011, Dähne et al. 2013) and seismic surveys (Thompson et al. 2013a, Pirota et al. 2014a). However, these studies generally focused upon harbor porpoises *Phocoena phocoena* and impact piling. Although these results can inform risk assessments for other species and piling techniques, they may increase conservatism as harbor porpoises are considered particularly responsive to anthropogenic disturbance (Tyack 2009, Tougaard et al. 2015). Many environmental assessments for coastal developments worldwide must consider potential impacts on both harbor porpoises and bottlenose dolphins *Tursiops truncatus*; both species have a worldwide distribution and are protected under the EU Habitats Directive (Hoyt 2012) and the U.S. Marine Mammal Protection Act. While bottlenose dolphin responses to other anthropogenic stressors such as boat traffic (e.g., Buckstaff 2004, Pirota et al. 2015) and dredging (Pirota et al. 2013) have been studied, no empirical data exist to permit comparison of species-specific responses to different pile driving noise sources.

Noise exposure assessments in coastal environments are also subject to uncertainty over noise propagation in shallow complex habitats (Jensen et al. 2011, Farcas et al. 2016), and baseline variability in ambient noise levels (Hildebrand 2009). Understanding of underwater noise propagation is underpinned by studies in oceanic waters (Urick 1983), where it is more reasonable to assume simple spherical spreading. In contrast, inshore marine mammal foraging habitats are often characterized by complex hydrography associated with finer-scale variation in coastlines, bathymetry, and freshwater inputs.

Here, we studied the responses of coastal bottlenose dolphins and harbor porpoises to piling noise during the extension of a harbor quay in NE Scotland. We used an array of passive acoustic monitoring (PAM) devices to compare spatio-temporal patterns of variation in the occurrence of both species within a baseline year prior to

construction (2013) and during the year of construction (2014). We also collected data on received levels of impact and vibration piling noise at different sites to optimize noise propagation models for this coastal area. These models were then used to predict received noise levels at different sites within our PAM array to relate observed variation in behavioral responses to predicted noise levels. Finally, data on ambient noise levels were analyzed to place reported noise levels from piling in a broader context.

METHODS

Study site and construction schedules

The study was conducted within the Moray Firth Special Area of Conservation (SAC), an area designated to protect a small population of bottlenose dolphins that range along the east coast of Scotland (Cheney et al. 2014). In 2014, construction works took place at the Nigg Energy Park (57°41.67' N, 4°1.91' W; Fig. 1) to extend an

existing quayside. This site is adjacent to the entrance to the Cromarty Firth, a core area within the SAC that is frequented by both bottlenose dolphins and harbor porpoises (Bailey et al. 2010a). Under the European Habitats Directive (92/43/EEC), this required an assessment of the potential impact of this new development upon the conservation status of the bottlenose dolphin population (Marine Scotland 2014b).

Construction work was carried out from 14th April to 24th October 2014 between 06:00 and 18:00 Greenwich Mean Time mostly using vibration piling techniques (Marine Scotland 2014a) but impact piling was required for some larger structural piles. The pattern of piling was highly variable, and on days when piling took place, the total duration per day ranged between 0.23 and 8.92 h (impact; median = 4.02 h) and 0.02 and 5.97 h (vibration; median = 1.49 h; Appendix S1: Table S1). Inspection of piling records provided by the developers revealed minor inconsistencies and missing data (with respect to the start and end

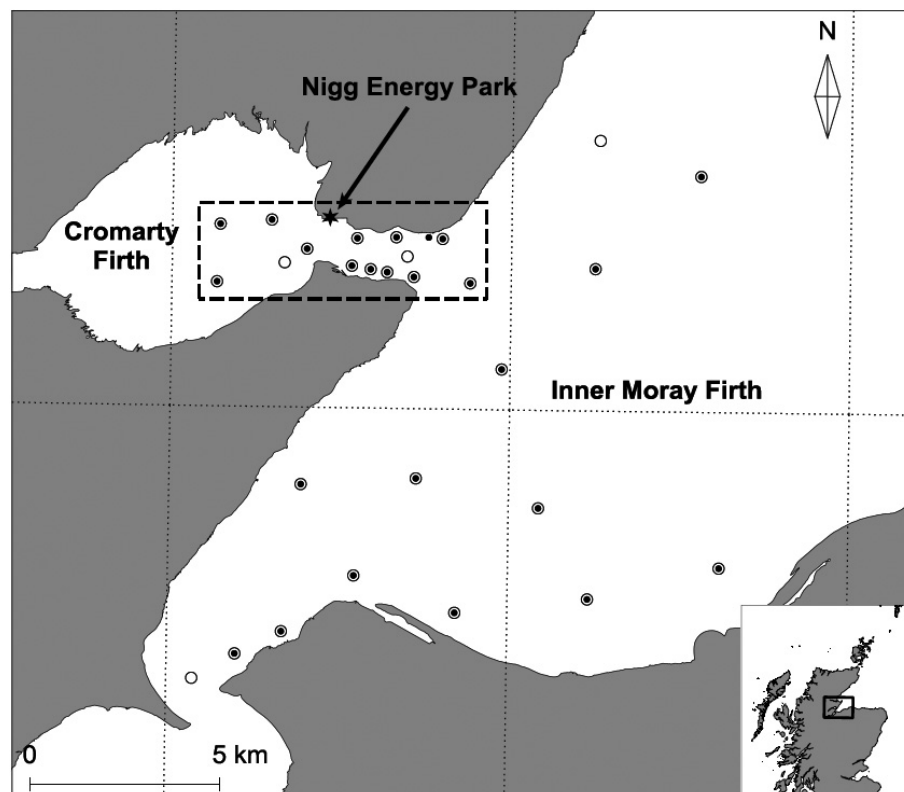


Fig. 1. Map of the study area showing the location of the Nigg Energy Park, the core study area (dashed box) in the Cromarty Firth and the CPOD sampling sites used in 2013 (open circles) and 2014 (black dots).

times of individual piling events) that potentially compromised analyses of fine-scale responses to variability in the duration of piling activity between days. Instead, we compared measures of dolphin and porpoise occurrence between days in which impact ($n = 13$) or vibration ($n = 123$) piling did or did not occur. This approach was consistent with regulator policy for evaluating and managing impact piling activity, where potential disturbance is considered in terms of “days of piling” (Marine Scotland 2014a).

Noise monitoring and analysis

Underwater noise levels were recorded at three locations (Fig. 2) using autonomous noise recorders (Wildlife Acoustics SM2M Ultrasonic, Wildlife Acoustics, Inc., Maynard, Massachusetts, USA). Recorders were independently calibrated as described in Merchant et al. (2014). Measurements were made at a sampling rate of 96 kHz, recording continuously at sites 2 and 3, and for 10 min/h at site 1. Data from sites 2 and 3 (Fig. 2) were analyzed in PAMGuide (Merchant et al. 2015) to determine received noise levels. These received noise levels were used to model piling source levels, taking account of local bathymetry, tide levels, and sediment types (Range-dependent Acoustic Model [RAM]; Collins 1993, Farcas et al. 2016). This enabled prediction of the received single-pulse SEL throughout the line-of-sight domain. See Appendix S2 for details of modeling work.

Ambient noise data from site 1 (Fig. 2) were available from hourly 10-min samples recorded between 1st July and 8th August 2014. This location was outside the line-of-sight area over which received levels could be reliably predicted (Fig. 2), but represents an area where previous studies recorded relatively high densities of encounters with bottlenose dolphins (e.g., Hastie et al. 2003, 2004). Variation in ambient noise levels (Root Mean Square [RMS] average in range 0.1–10 kHz) was compared in relation to piling as a factor, first during days (four levels: impact, vibration, both piling types, or no piling) and then at a finer scale during 10-min samples (three levels: impact, vibration, or no piling). Variation in daily ambient noise levels was modeled using a standard generalized linear model (GLM) assuming that noise levels were independent between days. Ambient noise levels from hourly samples were modeled using a Gaussian generalized estimating

equation (GEE)-GLM following the modeling procedure described below (using Julian day as the grouping factor in a working independence model autocorrelation structure, allowing model residuals from all samples within each day to be autocorrelated but assuming independence between days).

Assessing responses of cetaceans to piling activity

Spatio-temporal variation in the occurrence of dolphins and porpoises was studied using PAM in the baseline year prior to construction (2013) and the year of construction (2014). In each year, we used a series of fixed sampling sites in a core study area within the Cromarty Firth (where exposure to piling noise was expected to be highest) and in adjacent areas up to 15 km away (Fig. 1). We used CPODs (Chelonia Ltd., www.chelonia.co.uk; see Appendix S3 for full details) to monitor dolphin and porpoise echolocating behavior at 28 sites in 2013 and 25 sites in 2014 (Fig. 1).

At each site, data were summarized to assess potential impacts using three different metrics as response variables: first, the presence or absence of a species on each day of sampling (from 06:00 to 18:00); second, the number of hours in which each species was detected within that 12-h period (hereafter detection positive hours 12, or DPH12); and third, the duration of all dolphin and porpoise encounters that started between 06:00 and 18:00.

Data on cetacean occurrence in 2013 and 2014 were placed in a broader context using two sources of long-term monitoring data from this study site. First, CPOD data were available from a site at the entrance to the Cromarty Firth (Fig. 1) for a five-year baseline period (2009–2013). Second, capture–mark–recapture (CMR) estimates of bottlenose dolphin abundance within the Moray Firth SAC were available during the same five-year baseline period, and in 2014 (Cheney et al. 2014). Here, we also selected the subset of data from survey encounters that either started or ended within the Cromarty Firth study area (see the dashed rectangle in Fig. 1), and estimated the number of individuals using this smaller study area. This also provided information on the turnover of individuals through the 2014 construction period. See Cheney et al. (2014) for full details of survey protocols and CMR analysis.

We first assessed whether there was a seasonal trend in the dolphin and porpoise metrics

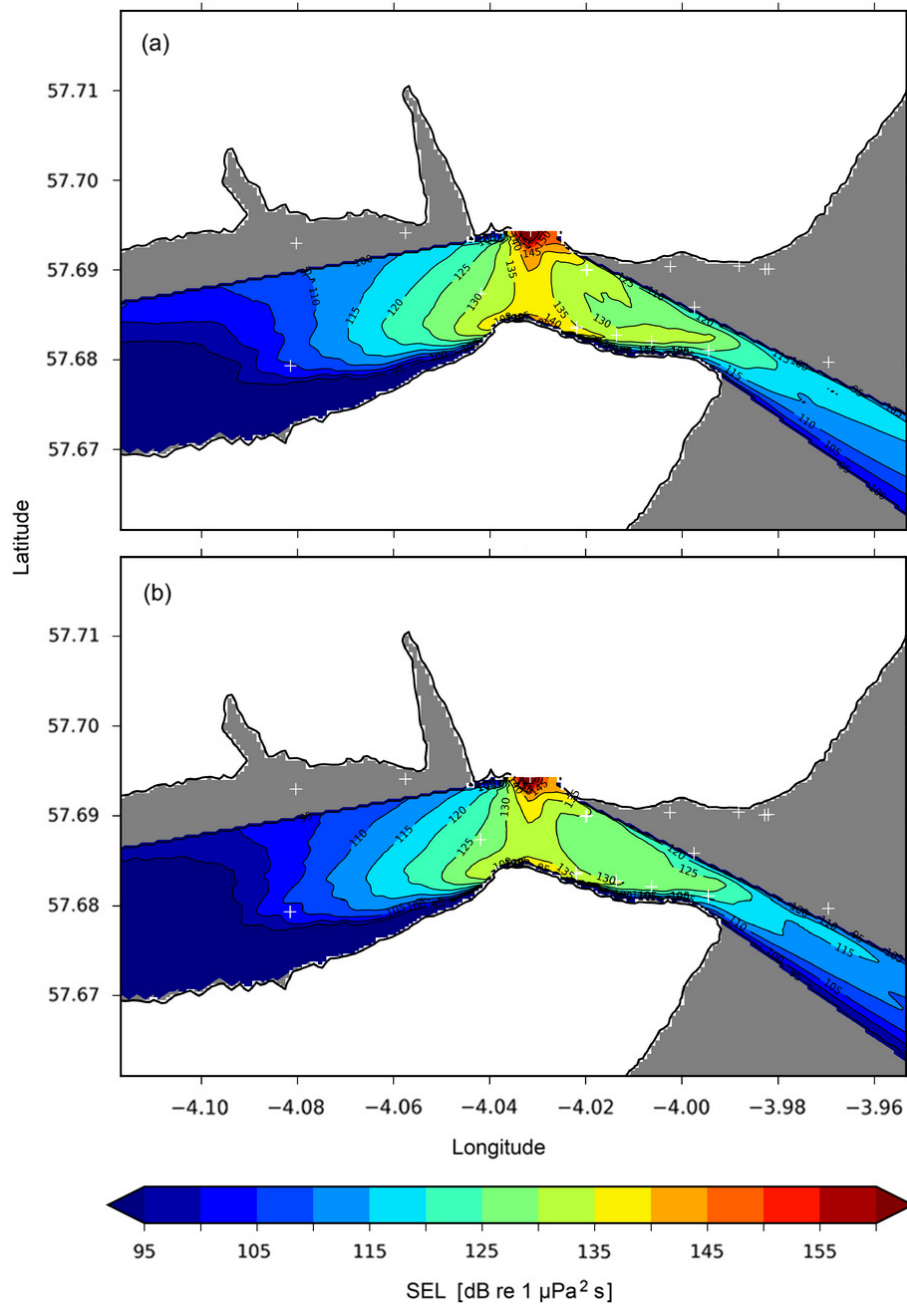


Fig. 2. Modeled predictions of received levels of noise from (a) impact piling and (b) vibration piling, within line of sight of the Nigg Energy Park. Predictions are (a) depth-averaged received single-pulse sound exposure level (SEL) for an impact strike and (b) depth-averaged one-second SEL for vibration piling.

using GEE-generalized additive models (GAMs) following the modeling procedure described below in the final paragraph of this section. We fitted an interaction with the factor Year to determine whether the seasonal trend differed

between baseline (2013) and impact (2014) years.

The effects of impact piling and vibration piling were then tested for all three metrics and both species in separate models at two temporal

and spatial scales (Appendix S4: Table S1). For analyses at the smaller spatial scale, only data from the subset of near-field CPOD locations within the Cromarty Firth were used, where noise levels were predicted to be highest and piling activity would be more detectable by animals (Fig. 1).

For the larger temporal-scale analysis, we tested whether or not impact or vibration piling caused a change in the dolphin and porpoise metrics in 2014 compared to 2013 (the baseline year), and at what spatial scale. We selected data from those dates in 2014 when there were (1) vibration piling and (2) impact piling, and compared these with data from the corresponding dates in 2013, when there was no piling. Models compared days in 2014 when a given type of piling occurred to the same days in 2013: (1) within the Cromarty Firth (interaction of factor Year with linear Distance from the source) or (2) over the entire array (interaction of factor Year with factor Area).

For the smaller temporal-scale analysis, using 2014 data only, investigation of the effects of vibration piling was constrained because there was strong collinearity between the seasonal trends in dolphin and porpoise metrics and vibration piling. We therefore restricted analyses at the smaller temporal scale to the effect of impact piling. We tested whether or not impact piling caused a change in the dolphin and porpoise metrics within 2014, and at what spatial scale. We selected data from those dates in 2014 when there was impact piling and compared these with data from those dates in 2014 when there was no impact piling. Models compared impact piling days in 2014 to days without impact piling in 2014: (1) within the Cromarty Firth (interaction of factor Piling with linear Distance from the source) or (2) over the entire array (interaction of factor Piling with factor Area).

We used GAMs to assess whether there was any seasonal trend in the dolphin and porpoise metrics (Wood 2006), by fitting Julian day as a B-spline with four degrees of freedom, with one internal knot positioned at the mean value. We used GLMs (Nelder and Wedderburn 1972) to assess the effect of piling activity on the dolphin and porpoise metrics at both temporal and spatial scales. We used binary GLMs (with a logit link) to model animal presence and absence, Poisson GLMs (with a log link) for the DPH12 response

variable, and gamma GLMs (with a log link) for encounter duration (a non-negative continuous response variable). Given the spatial pattern of our sampling sites and known CPOD detection ranges, we did not expect the dolphin and porpoise metrics to be spatially independent; therefore, all models were fitted using GEEs (Liang and Zeger 1986, Hardin and Hilbe 2003) implemented in R [R Development Core Team 2015] using the library *geepack*. Julian day of each year was used as the grouping factor, allowing model residuals from all sites within each day to be autocorrelated. We tested the autocorrelation structures for the residuals available in the *geepack* library using the quasi-likelihood under the independence model criterion, or QIC (Pan 2001). An approximate version of the QIC, the QICu, was used to assess whether variables should be retained or not in the model (Pan 2001). The significance of the covariates was assessed using Wald's tests based on robust GEE-estimated standard errors (Hardin and Hilbe 2003). Distance from source (the minimum at-sea distance between each CPOD and the piling location in meters) was modeled as a linear term, and the remaining covariates were included as factors: Year (two levels, 2013 and 2014); Piling (two levels, piling or no piling); and Area (two levels, within the Cromarty Firth or outside the Cromarty Firth; see Fig. 1).

RESULTS

Characterization of piling noise

Median peak-to-peak source levels from measurements of 10 hammer strikes on 1st July 2014 were estimated to be 240 dB re 1 μ Pa (range = 8 dB), with a single-pulse SEL source level of 198 dB re 1 μ Pa² s. The broadband r.m.s. source level based on two 6-s samples of vibration piling on 15 April 2014 was estimated to be 192 dB re 1 μ Pa. See Appendix S5: Fig. S1, for example, waveforms; Appendix S5: Fig. S2 for frequency spectra; and Audio S1 and Audio S2 for sample audio files. Using the impact piling data to optimize the acoustic propagation model, spatial variation in received single-pulse SEL was predicted within line of sight of the piling location (Fig. 2; Appendix S6: Tables S1, S2).

Acoustic recordings from site 1, at the entrance to the Cromarty Firth, indicated that broadband ambient noise levels did not vary significantly

between days in which piling (impact, vibration, or both piling types) did or did not occur ($\chi^2_3 = 4.98$, $P = 0.17$).

Using the developer's piling records (Appendix S1: Table S1), we identified 10-min samples from 386 h when there was no piling, 58 h with vibration piling, and 19 h with impact piling. At this finer scale, the analysis showed that piling activities increased hourly broadband noise levels significantly ($\chi^2_2 = 7.02$, $P = 0.03$; Fig. 3). However, noise levels in hours with impact piling did not differ from those in hours with vibration piling, but the sample size was small (58 h with vibration and 19 h with impact piling).

Responses of cetaceans to piling activity

Bottlenose dolphins were detected on most days in 2013 and 2014, whereas harbor porpoise occurrence was generally lower (Fig. 4). Modeling identified seasonal trends in the occurrence of both species for all three response metrics, although the fine-scale detail of seasonal patterns varied between 2013 and 2014 ($P < 0.001$ for the interaction between seasonal trend and year, for all models). The general trend was for a decrease in bottlenose dolphins and an increase in harbor porpoises from May to October.

Long-term data from the Cromarty Firth site confirmed that seasonal patterns seen during 2014 were within baseline levels for the previous five years, with a summer increase in dolphin occurrence and winter peak in porpoise occurrence

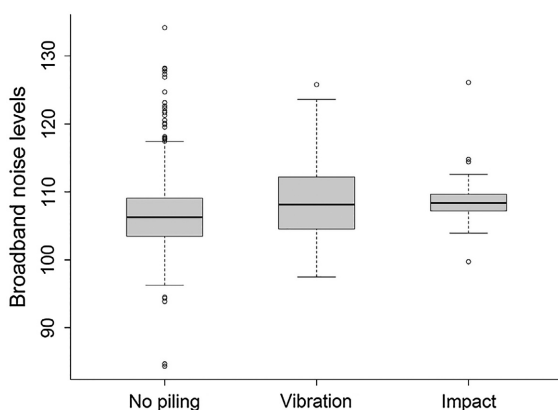


Fig. 3. Averaged broadband (0.1–10 kHz) RMS ambient noise levels at site 1 during 10-min samples in which there were no piling, vibration piling, and impact piling.

(Fig. 5). Similarly, the estimated abundance of bottlenose dolphins within the Cromarty Firth did not differ from the abundance estimate for the SAC in 2014 and was comparable to the five-year baseline abundance estimates in both areas (Fig. 6). The individual sightings matrix illustrates that the same individuals were observed regularly in the Cromarty Firth through the summer until the end of August 2014 (Appendix S7: Table S1 and Fig. S1).

While overall abundance in the study area during 2014 was similar to baseline, more detailed analysis detected responses of bottlenose dolphins to impact piling activity using 2013 data as the control. All three metrics were lower in the Cromarty Firth during days on which piling occurred, but this effect was only retained by model selection and significant for the duration of encounters (Appendix S4: Table S2). Here, the significant interaction between year and area indicates that encounters decreased by 237 s on average within the Cromarty Firth on days when dolphins were exposed to impact piling noise, whereas encounter duration at sites outside this area increased by 277 s on average (Fig. 7c). At the smaller spatial scale, there was no support for models that included distance from piling location within the Cromarty Firth as a potential covariate explaining any of the spatial variation in encounter duration (Appendix S4: Table S2). For harbor porpoises, year had a significant effect on both DPH12 and encounter durations (Fig. 7h, i), but the lack of a significant interaction with area suggests that this was not related to impact piling activity (Appendix S4: Table S2). Analysis of the effect of impact piling on dolphin and porpoise occurrence at the smaller temporal scale using 2014 data alone gave very similar results (Appendix S4: Table S3).

Significant year–area interactions were also detected for the probability of occurrence of both bottlenose dolphins (Fig. 7d) and harbor porpoises (Fig. 7j) on days in which vibration piling took place (Appendix S4: Table S2). For bottlenose dolphins, this interaction was also significant for encounter duration (Fig. 7f) but effect sizes were extremely small and confidence intervals for both significant metrics overlapped. The effect of vibration piling on harbor porpoise occurrence appeared slightly stronger (Fig. 7j), but even this reduction was relatively small.

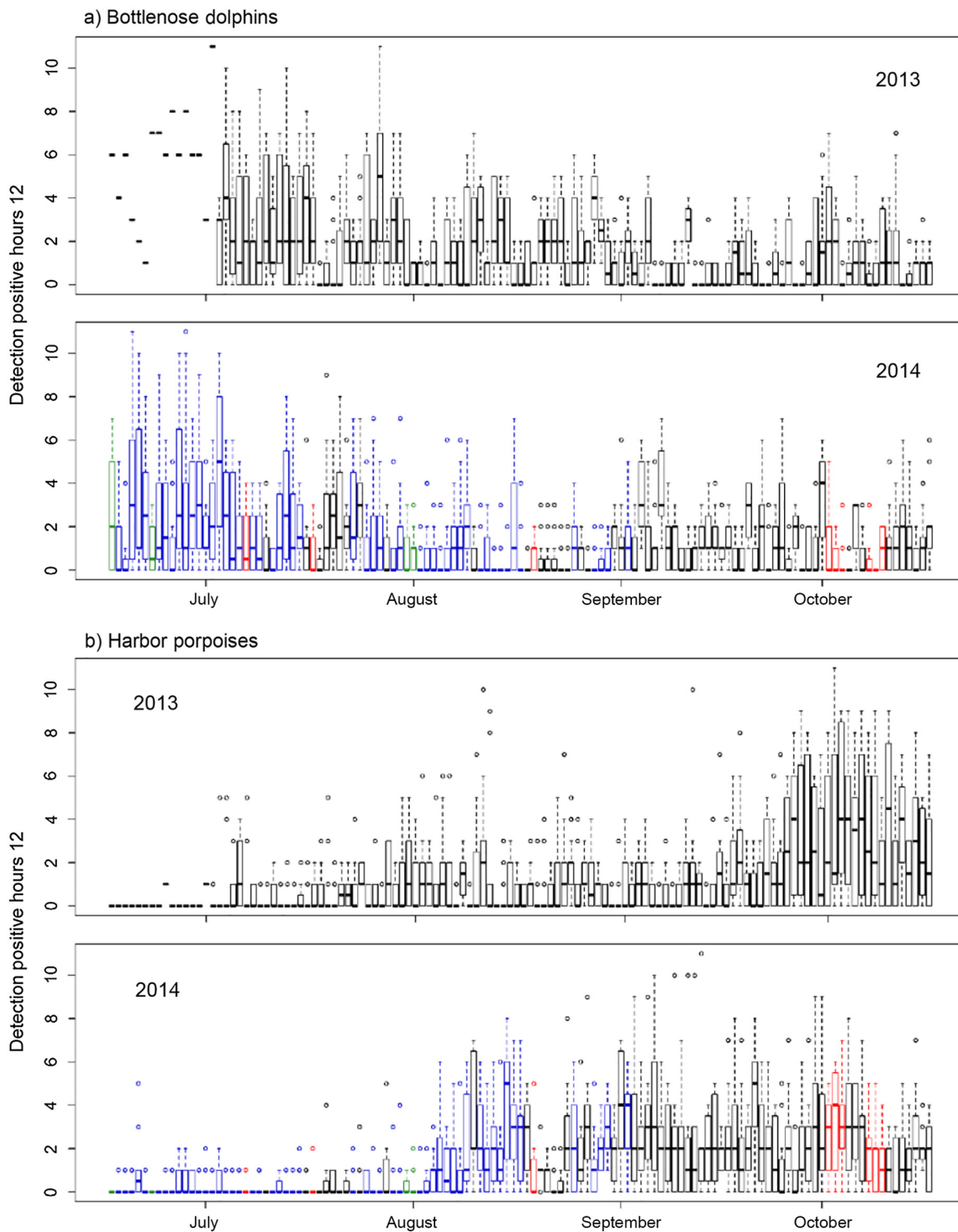


Fig. 4. Seasonal variation in the median number of hours during daytime (with interquartile ranges) that (a) bottlenose dolphins and (b) harbor porpoises were detected on CPODs within the Cromarty Firth in the summers of 2013 and 2014. Days when piling occurred in 2014 are colored: red for impact piling; blue for vibration piling; green for days where both vibration and impact piling took place.

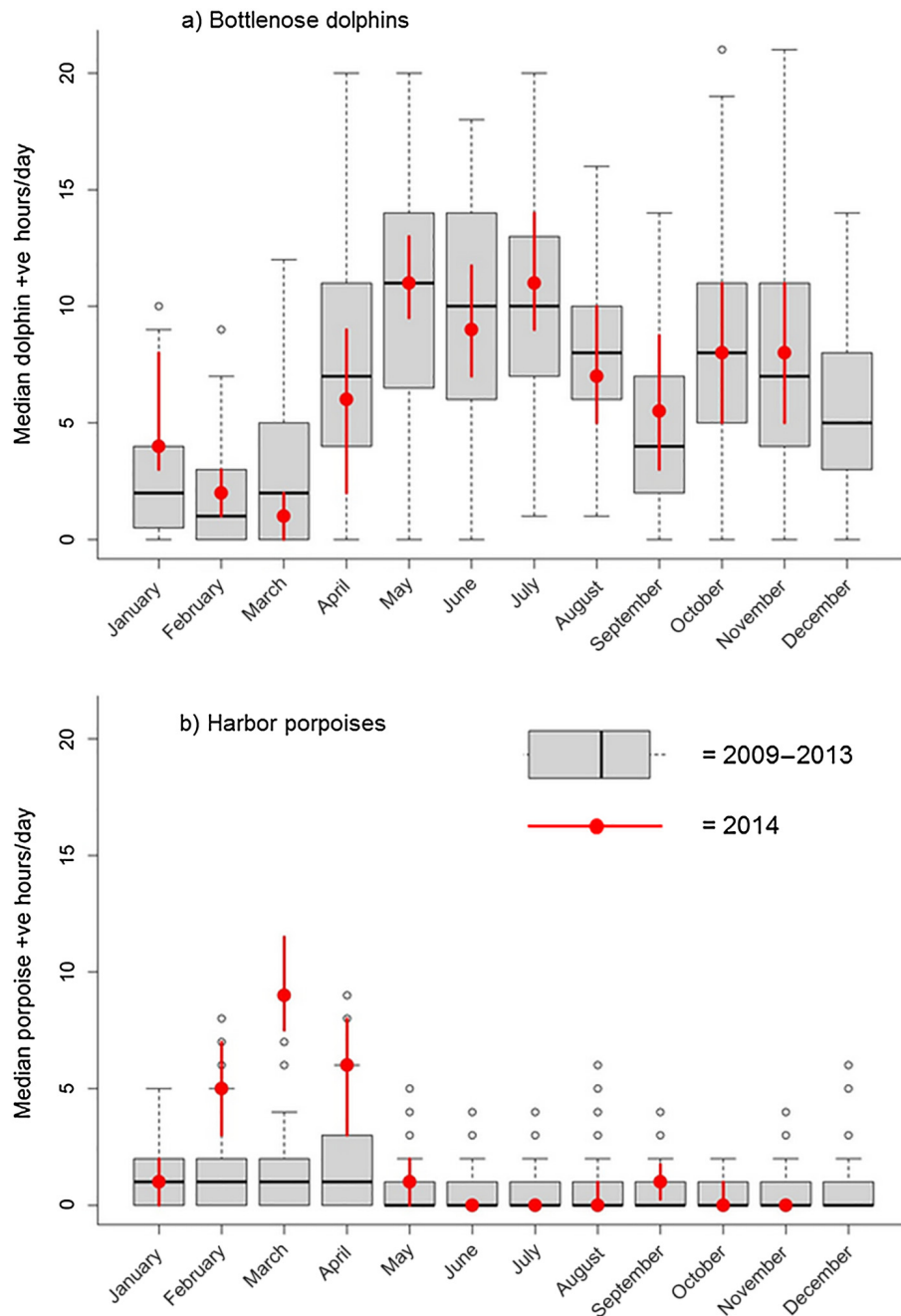


Fig. 5. Monthly variation in the median number of hours (with interquartile ranges) that (a) dolphins and (b) porpoises were detected at the long-term study site within the Cromarty Firth.

DISCUSSION

The effective regulation of activities producing underwater noise remains constrained by uncertainty about the spatial and temporal scales over

which marine mammals may be displaced (Southall et al. 2007). This can prove especially challenging when balancing environmental and socio-economic costs of potential mitigation measures (Nehls et al. 2007, Jefferson et al. 2009).

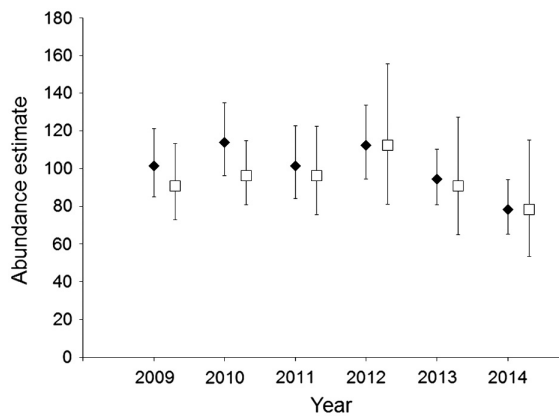


Fig. 6. Abundance estimate of bottlenose dolphins in the Special Area of Conservation (black diamonds) and the Cromarty Firth (clear squares) each year (2009–2014).

Our study indicated that two protected cetacean species were not completely displaced by impact or vibration piling in a coastal habitat. While less overt effects of disturbance were detected, effect sizes were small, probably as a result of the much lower received broadband noise levels in our study area compared to those recorded in previous studies of impact piling offshore. Anticipated differences in the extent of responses to impact and vibration piling were not realized. Only bottlenose dolphins showed a measurable (but weak) behavioral response to both impact and vibration piling, reducing the amount of time that they spent around the construction works during piling (Fig. 7). The similarity in responses to vibration and impact piling was perhaps due to the unexpectedly high source level of vibration piling (192 dB re 1 μ Pa) compared to impact

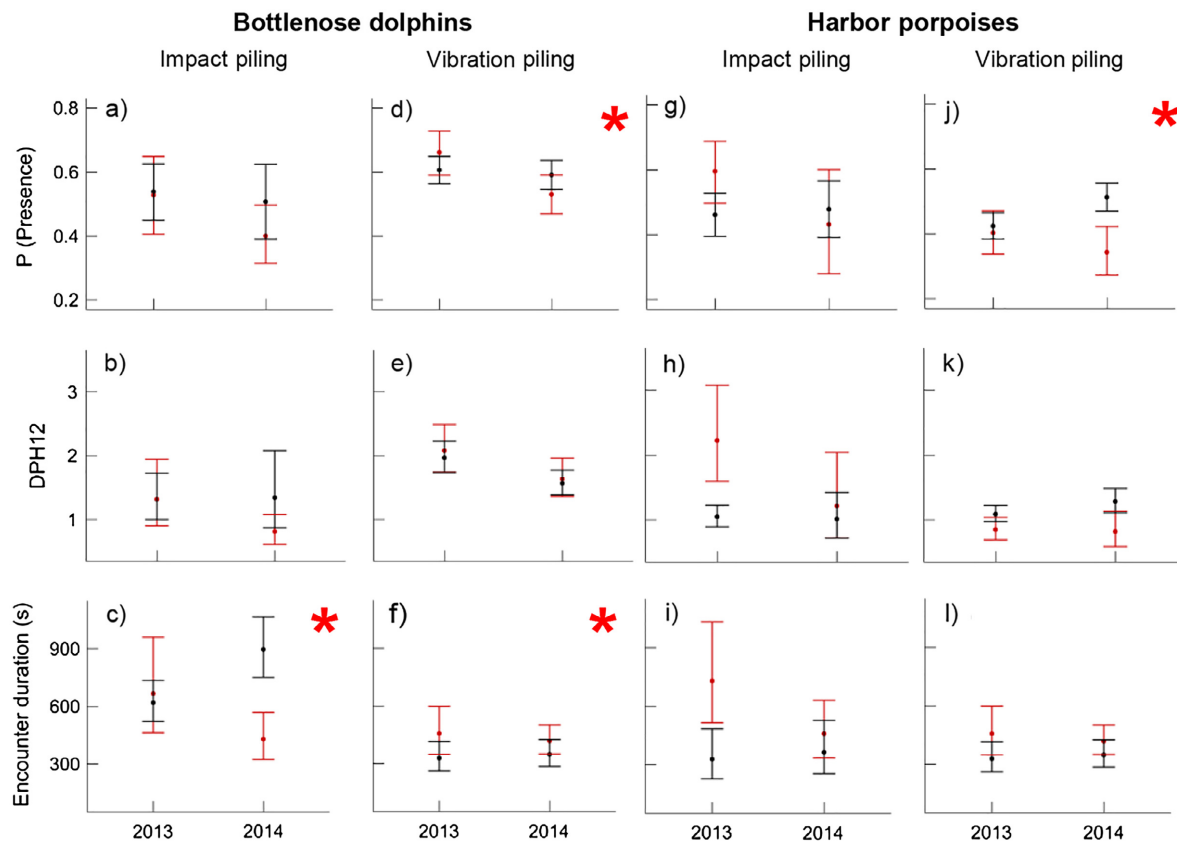


Fig. 7. Comparison of the effect of impact and vibration piling on three metrics of bottlenose dolphin and harbor porpoise occurrence determined from passive acoustic monitoring within the Cromarty Firth (in red) and outside the Firth (in black) in 2013 (no piling) and 2014 (piling). Red asterisks indicate statistically significant interactions between year and area.

piling (198 dB re 1 $\mu\text{Pa s}$), and the strongly pulsed sound signature of the vibration piling (Appendix S5: Fig. S1b), which was more comparable to impact piling than previously thought. These findings re-affirm the need to carefully consider potential impacts of noise on cetaceans during coastal infrastructure developments, particularly as displacement by impact piling was more limited than expected from previous studies (Schuster et al. 2015), and vibration piling had greater impacts than anticipated. This could be particularly important if the use of vibration piling to mitigate perceived impacts of impact piling extends the overall construction period. Other management implications depend critically upon whether these findings reflect genuine differences in the sensitivity of these two species, or differences in methodology, the nature and scale of the noise sources, or ecological context.

Methodological considerations

Studies of small cetacean responses to underwater noise have typically been limited to short-term investigations using echolocation click detectors (Carstensen et al. 2006, Brandt et al. 2011, Dähne et al. 2013). This approach assumes that variations in acoustic activity reflect changes in relative density and these, in turn, reflect cumulative individual responses to the noise source. Studies integrating acoustic and visual survey methods provide increasing support for this approach (Dähne et al. 2013, Thompson et al. 2013a, Williamson et al. 2016). However, some variation in acoustic detections may result from changes in behavior rather than animal density (Pirrotta et al. 2014a, b), but these methodological issues are common both to our study and earlier studies of harbor porpoise responses.

All these studies share the challenge of identifying appropriate controls when considering responses to industrial developments. This is constrained by logistic and commercial issues, as well as the inherent variability in natural systems involving highly mobile marine predators. Here, we analyzed cetacean responses at two spatial and two temporal scales, but there was strong collinearity between the seasonal trends in cetacean occurrence and vibration piling activity. Consequently, we were unable to test for the effect of vibration piling using only 2014 data, and our analyses at the smaller temporal scale were

constrained to the effects of impact piling (Appendix S4: Table S3). Finer-scale analyses were also not possible due to lack of detail on the timing of piling in reports to regulators. Nevertheless, results from both spatial and temporal scales used in our study were consistent, providing evidence that impact and vibration piling significantly influenced some measures of dolphin occurrence, but effect sizes were small and seasonal occurrence remained within baseline variability observed during the previous five years. While baseline levels in dolphin occurrence were relatively high and consistent between years (Fig. 5a), porpoise occurrence was much lower (Fig. 5b). Consequently, any comparison of responses was also constrained by species-specific differences in statistical power. Previous studies of porpoises have generally been undertaken in offshore sand-bank habitats where higher baseline densities would have improved the potential to detect finer-scale responses in this species. Similarly, the large difference in the number of days of impact piling compared to vibration piling reduced the power to detect differences in responses to the two piling methods and increased the chances of detecting significant effects for vibration piling.

The nature and scale of noise disturbance

Studies of anthropogenic noise on cetaceans require measured or modeled estimates of the received levels experienced by their subjects (e.g., DeRuiter et al. 2013, Isojunno et al. 2016). Without this information, interpretation of the response, or lack of response, to a particular source of sound is difficult (Nowacek et al. 2007), preventing translation of findings into management advice or regulations. Here, we recorded levels of impact piling noise at two locations, enabling us to predict received sound exposure levels (SEL) throughout the line-of-sight domain. The median peak-to-peak source level of 240 dB re 1 μPa was comparable to impact piling of 4-m monopiles at an offshore wind-farm (peak-to-peak source level 235 dB re 1 μPa^2 ; Tougaard et al. 2009). However, predicted received single-pulse broadband SEL values within 1 km of the piling site were much lower in our shallow water study area: 133.4 dB re 1 $\mu\text{Pa}^2 \text{ s}$ at 812 m compared to 176 dB re 1 $\mu\text{Pa}^2 \text{ s}$ at 720 m (Brandt et al. 2011) and 164–170 dB re 1 $\mu\text{Pa}^2 \text{ s}$ at 750 m (Dähne et al. 2013). Despite similar source levels, differences in local propagation characteristics may

explain the lower response by harbor porpoises in our study area. This highlights the need for further research in other areas and the importance of using appropriate underwater noise modeling to develop site-specific environmental assessments (Farcas et al. 2016).

Observed fine-scale behavioral responses by dolphins to piling occurred at predicted received single-pulse SEL values of between 104 and 136.2 dB re $1 \mu\text{Pa}^2 \text{ s}$ for impact piling and between 98.8 and 131.7 dB re $1 \mu\text{Pa}^2 \text{ s}$ for vibration piling (Appendix S6: Tables S1, S2). Only two studies previously examined behavioral responses of dolphins to pile driving. Wursig et al. (2000) found no significant change in abundance of *Sousa chinensis* during harbor construction works, but dolphins increased travel speeds during piling. Their noise measurements are not directly comparable, but estimated received levels were 7–9 dB lower in our study area (Appendix S6: Table S1). Paiva et al. (2015) detected fewer surfacing *Tursiops aduncus* during piling at received levels similar to those recorded in our study.

Variations in responses to anthropogenic noise may also result from differences in signal-to-noise ratio, highlighting the importance of parallel estimates of ambient noise. Broadband ambient noise levels within our study site did not differ between piling and non-piling days, although ambient noise levels were higher during hours with piling. Modeling indicated that piling noise propagation was strongly influenced by the complex bathymetry at the site, and received noise levels deviated substantially from a simple range-based relationship (Fig. 2). These predictions were confirmed by measurements, potentially explaining the lack of a gradient in responses with increasing distance from source. A gradient in harbor porpoise responses to pile driving during offshore wind farm construction was observed in some (Brandt et al. 2011, Dähne et al. 2013) but not all previous studies (Carstensen et al. 2006, Tougaard et al. 2009). A possible explanation for a lack of gradient in responses with increasing distance is that animals respond primarily to the novelty of the sound, rather than absolute noise level or signal-to-noise ratio, as seen among dolphins that responded to boat physical presence but not noise levels (Pirota et al. 2015).

The ecological context of disturbance responses

Behavioral responses to anthropogenic noise may vary in relation to species, individual condition, habitat, context, and previous exposure to noise (Gill et al. 2001, Beale and Monaghan 2004, Southall et al. 2007, Ellison et al. 2012). Our study area has a long history of exposure to anthropogenic noise from oil and gas activities, fisheries, and shipping (Halpern et al. 2008, Thomsen et al. 2011). Consequently, individual porpoises and dolphins using the Moray Firth may have habituated to, and/or become more tolerant of, anthropogenic noise compared to those in less heavily impacted areas, potentially contributing to the weak behavioral responses to pile driving. Additionally, vibration piling occurred almost daily during the five-month study. Responses of harbor porpoises to airgun noise declined during a shorter (10-d) seismic survey (Thompson et al. 2013a). As for all previous passive acoustic studies of harbor porpoise responses, interpretation of these changes was constrained by uncertainty over whether or not the same individuals were exposed in different phases of the study. In contrast, repeated sightings of recognizable bottlenose dolphins confirmed that some individuals continued to use the impacted area throughout the construction period (Appendix S7: Table S1). Our study design did not permit us to determine whether or not habituation was occurring. However, if tolerance levels did increase through time, estimates of the mean response for the entire study period may underestimate initial responses of naïve individuals.

Harbor porpoises are considered particularly sensitive to underwater noise (Tyack 2009, Tougaard et al. 2015). While there was a slightly stronger effect of vibration piling on harbor porpoise occurrence, their overall weaker response to impact and vibration piling compared to bottlenose dolphins was not expected. This could have been due to low statistical power, or variations in response could result from differences in ecological context. Thus, the availability of alternative habitat and relative predation risk could have influenced responses to disturbance (Gill et al. 2001, Frid and Dill 2002). During baseline studies in 2013, all three metrics for dolphin occurrence were similar in both the core and the wider study area, whereas porpoise occurrence metrics were higher within the core area (Fig. 7).

During impact piling in 2014, dolphins increased their use of unexposed areas, whereas porpoises did not. While bottlenose dolphins may appear more susceptible to impact piling noise than harbor porpoises, harbor porpoise responses may be constrained due to a higher mortality risk from dolphin attacks (Ross and Wilson 1996) in alternative areas (Frid and Dill 2002, MacLeod et al. 2007).

Finally, apparent differences in the strength of porpoise responses to impact piling noise in this and previous studies may result from the use of additional mitigation measures. Earlier work was conducted during windfarm construction where acoustic deterrent devices (ADDs) were used to displace individuals and minimize near-field injuries. Consequently, reported responses to piling were cumulative responses to pile driving noise and ADD deployment (Brandt et al. 2011, Dähne et al. 2013). Acoustic deterrent devices are known to have far-reaching effects in the absence of piling noise (Brandt et al. 2013a, b). Efforts to optimize assessment and mitigation measures during anticipated increases in coastal construction activity (Bulleri and Chapman 2010) therefore require better understanding of the relative influence of different high-frequency (ADD) and lower-frequency piling noise sources on behavioral responses.

CONCLUSIONS

Previous studies of the behavioral responses of harbor porpoises to pile driving have typically observed a short-term reduction in porpoise detections within 20 km of the piling site, leading to an expectation that impact pile driving will cause significant displacement of porpoises. The lack of a strong behavioral response to both types of piling by either species observed in this study shows that this is not always the case and suggests that in certain circumstances management measures to mitigate displacement should be reviewed. Our results also emphasize the need for better understanding of the noise levels and behavioral responses to vibration piling before recommending its use to mitigate impact piling. Most importantly, our study exposes a need to examine each development separately, using appropriate noise modeling techniques to better predict noise exposure, particularly at sites with differing or complex bathymetry, thereby avoiding overly conservative license

consent conditions. This study provides stakeholders, including developers, managers, and regulators, with scientific evidence on the behavioral responses of bottlenose dolphins and harbor porpoises to piling noise from both impact and vibration piling at a coastal site. As such, our results will inform risk assessments, policy frameworks, and mitigation plans associated with the planning and licensing of coastal developments.

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DATA AVAILABILITY

Data have been made available in the Dryad repository at <https://doi.org/10.5061/dryad.g3603>.

SUPPORTING INFORMATION

Additional Supporting Information may be found online at: <http://onlinelibrary.wiley.com/doi/10.1002/ecs2.1793/full>