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Disturbance of harbour porpoises during construction of the first seven offshore wind farms in Germany

Miriam J. Brandt[1,*], Anne-Cecile Dragon[1], Ansgar Diederichs[1], Michael A. Bellmann[2], Veronika Wahl[3], Werner Piper[4], Jacob Nabe-Nielsen[5], Georg Nehls[1]

[1]BioConsult SH GmbH&Co.KG, 25813 Husum, Germany
[2]Institute of Technical and Applied Physics (itap) GmbH, 26129 Oldenburg, Germany
[3]IBL Umweltplanung GmbH, 26122 Oldenburg, Germany
[4]Institute for Applied Ecosystem Research (IfAÖ) GmbH, 20357 Hamburg, Germany
[5]Department of Bioscience, Section for Marine Mammal Research, Aarhus University, 4000 Roskilde, Denmark

ABSTRACT: We investigated the disturbance effects of offshore windfarm construction on harbour porpoises *Phocoena phocoena* using acoustic porpoise monitoring data and noise measurements during construction of the first 7 large-scale offshore wind farms in the German Bight between 2010 and 2013. At 6 wind farms, active noise mitigation systems (NMS) were applied during most piling events, and 1 was constructed without. Based on generalized additive modelling analyses, we describe a clear gradient in the decline of porpoise detections after piling, depending on noise level and distance to piling. Declines were found at sound levels exceeding 143 dB re 1 µPa^{2}s (the sound exposure level exceeded during 5% of piling time, SEL_{05}) and up to 17 km from piling. When only considering piling events with NMS, the maximum effect distance was 14 km. Compared to 24–48 h before piling, porpoise detections declined more strongly during unmitigated piling events at all distances: at 10–15 km declines were around 50% during piling without NMS, but only 17% when NMS were applied. Within the vicinity (up to about 2 km) of the construction site, porpoise detections declined several hours before the start of piling and were reduced for about 1–2 d after piling, while at the maximum effect distance, avoidance was only found during the hours of piling. The application of first generation NMS thus reduced the effect range of pile driving and led to a lower decline of porpoise detections over all distances. However, NMS were still under development and did not always work with equal efficiency. As NMS have further developed since, future investigations are expected to show additional reduction of disturbance effects.

KEY WORDS: Acoustic monitoring · Acoustics · Anthropogenic impact · Behaviour · Marine mammal · PAM · *Phocoena phocoena* · Spatial scale · Wind turbine · Pile driving

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INTRODUCTION

In Europe, offshore wind energy is rapidly developing as an alternative energy source to nuclear power and fossil fuels. Since the opening of the world's first offshore wind farm (OWF), Vindeby in Denmark, in 1991, construction increased rapidly, especially from 2009, with 81 wind farms and 3589 turbines in operation in European waters by the end of 2016 with a production capacity of about 12 631 MW (Pineda & Tardieu 2017). While this is considered an important step towards more environmentally

*Corresponding author: m.brandt@bioconsult-sh.de

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friendly power production, concern has been raised about potential negative impacts of construction and operation of wind turbines on the marine environment (Madsen et al. 2006). Much of this concern addresses the effects on marine mammals that are influenced by pile driving noise generated during construction of the wind turbines (Carstensen et al. 2006, Tougaard et al. 2009, Bailey et al. 2010, Thompson et al. 2010, Brandt et al. 2011, Dähne et al. 2013). A key species in this respect in Northern Europe is the harbour porpoise *Phocoena phocoena*, which is listed as a protected species in Annex IV of the Council Directive 92/43/EEC. Due to their widespread occurrence in the North and Baltic Seas, harbour porpoises are likely present in every European OWF constructed to date (Gilles et al. 2009, Peschko et al. 2016, Hammond et al. 2017). Because of their high dependency on echolocation for orientation and foraging, harbour porpoises are vulnerable to noise-generating anthropogenic activities (Madsen et al. 2006, Lucke 2010, Tougaard et al. 2015).

Most turbines constructed to date have been placed on steel foundations that were driven into the sea floor using large hydraulic hammers. This pile driving operation causes large underwater noise emissions that can be detected up to 70 km from the source (Bailey et al. 2010). At short range, noise levels can induce physiological effects such as temporary or permanent increases in the hearing threshold (temporary threshold shift and permanent threshold shift; Southall et al. 2007, Lucke et al. 2009, Kastelein et al. 2016). At noise levels where physiological injury is no longer a concern, noise can still interfere with the animals' ability to orientate, communicate and forage or simply be perceived as unpleasant, likely causing avoidance behaviour (Ellison et al. 2012, Harris et al. 2018). This may then cause a decrease in energy intake via lost feeding time (Nabe-Nielsen et al. 2018, Wisniewska et al. 2018). In some cases, noise may also cause a decrease in foraging efficiency, even when porpoises are not deterred (Pirotta et al. 2014). Being a small marine mammal with a low volume to surface ratio and living in cold to temperate waters, a porpoise's metabolic expenditure is relatively high and it may therefore have to consume about 10% of its body weight each day (Kastelein et al. 1997, Lockyer et al. 2003). This high energy expenditure together with little capacity for energy storage makes porpoises more vulnerable to starvation, and hence to pile driving noise, than many other cetaceans (Wisniewska et al. 2016).

It is difficult to judge at what level disturbance by noise affects an individual's fitness (Christiansen & Lusseau 2015) and at what point population level consequences are to be expected. It therefore seems sensible to focus on the onset of avoidance behaviour, which is relatively easy to detect and which leaves little doubt as to cause and effect if observed directly after the onset of a given stimulus. Having to allocate time to swimming away from disturbance also compromises time that may otherwise be spent foraging, especially if an animal was engaged in foraging when being disturbed and must now invest time to find a new profitable foraging location.

Harbour porpoises are difficult to study using visual observations, because of their small size, relatively cryptic behaviour and far-ranging movements. Visual methods are also highly dependent on prevailing weather conditions, which makes it almost impossible to time them precisely to particular construction activities. Studies looking at construction effects on porpoises have therefore mainly used passive acoustic monitoring, in most cases applying the 'T-POD', or its successor the 'C-POD', specially designed to record harbour porpoise echolocation clicks (Chelonia Ltd.; Tregenza et al. 2016). This method enables the collection of long time series of porpoise presence data that can be related to the presence of construction activities. A decrease in porpoise detections does not necessarily indicate avoidance behaviour, but could also result from changes in acoustic behaviour. However, there is now considerable evidence for a direct link between acoustic porpoise recordings and porpoise densities (Sveegaard et al. 2011, Kyhn et al. 2012, Brandt et al. 2013b, Dähne et al. 2013, Williamson et al. 2016).

Several studies using PODs to look at the distances over which porpoises are disturbed by pile driving during wind farm construction found effects of piling without active noise mitigation systems (NMS) at distances up to 15–20 km from the construction site (Carstensen et al. 2006, Tougaard et al. 2009, Brandt et al. 2011, Dähne et al. 2013). However, study design, data availability and analysis methods varied substantially between these studies, so results may not be directly comparable. In some studies, data from crucial distances were also not available, making it difficult to estimate the exact disturbance range. Furthermore, not all studies involved acoustic measurements of piling noise, or there was too much uncertainty concerning transmission loss over larger distances. Consequently, no conclusions could be drawn about the noise levels at which porpoises started to avoid piling noise. Dähne et al. (2013) only gave a relatively broad range, of between 139 and 152 dB re 1 µPa^{2}s sound exposure level (SEL), at which a reaction from porpoises was found. During an experimental study on captive animals, Kastelein et al. (2013) observed a significant increase in jumping frequency of harbour porpoises when exposed to playback noise of pile driving at an SEL of 145 dB re 1 μPa^{2}s. However, whether this threshold corresponds to conditions observed in the field is uncertain. A recent review by Tougaard et al. (2015), taking into account several studies on porpoise reaction to different sources of anthropogenic noise and the frequency spectrum of the noise given in these studies (which usually reported unweighted broad band noise levels), confirmed that behavioural reactions of porpoises are dependent on the frequency spectrum of the noise. They suggested that behavioural reactions are usually found at about 40–50 dB above the frequency-specific hearing threshold. Analysing field data and linking reaction distances to the perceived noise level is required to draw general conclusions on the reactions of porpoises to piling noise.

No common regulation exists within the EU requiring noise mitigation for OWF construction. Only some countries, including Germany, Denmark and Belgium, have issued regulations, which force wind farm developers to reduce noise emission by active mitigation. Some of the strictest regulations in the EU were put in place by the German government, with permits for new OWF only being issued under the condition that levels for impulsive noise do not exceed 160 dB re 1 μPa^{2}s for the SEL exceeded during 5% of piling time (SEL_{05}) at 750 m from the piling location and that marine mammals are to be deterred from the vicinity of the construction site prior to piling by using acoustic deterrence devices such as a seal scarer and by using a soft start procedure. This aims at avoiding the temporary threshold shift in porpoises, which is considered a physical injury. In the context of the 'Schallschutzkonzept' (concept for noise protection), published by the Federal Ministry for the Environment, Nature Conservancy, Building and Nuclear Safety in 2013 (BMU 2013) this 160 dB threshold at 750 m distance from piling was confirmed. It was further argued that an SEL of 140 dB re 1 μPa^{2}s should be used as a precautionary criterion for disturbance effects and that disturbance by pile driving reaches up to about 8 km if piling noise is 160 dB at 750 m distance. Consequently, to meet this threshold and reduce disturbance effects, all but the first large OWF in Germany were constructed under the use of various NMS. Great effort, in terms of finance, research and offshore logistics, was invested into designing and planning their effective application. The rationale for this massive investment was primarily the avoidance of injury to harbour porpoises, but it was also expected to reduce the range at which porpoises reacted to noise, and ideally also the duration of these avoidance effects.

During the construction of all 7 OWFs constructed in the German North Sea between 2010 and 2013, extensive monitoring programmes collected data on porpoise presence and acoustic data. Combining these data in a joint and cross-project analysis offers a unique opportunity to comprehensively study the pile driving impact on harbour porpoises within the whole German North Sea over a period of 4 yr. As in all other studies on the effect of piling noise on harbour porpoises in Denmark and Germany, a seal scarer was deployed prior to piling at every construction project. Therefore, it is not possible to entirely tease apart effects from deterrence and piling. However, effect ranges of the seal scarer were found up to 7.5 km in the German North Sea (Brandt et al. 2013b), and effects found at larger distances are therefore unlikely to be caused by only deterrence (Brandt et al. 2011).

For the present study, we analysed passive acoustic monitoring data collected during these 7 OWF projects in combination with underwater noise measurements during piling activities. Our aims were to draw general conclusions about (1) porpoise avoidance distances during wind farm construction in the German North Sea, (2) the duration of avoidance, (3) the noise levels at which porpoises show avoidance behaviour and finally (4) whether the application of NMS led to a reduction in disturbance effects.

MATERIALS AND METHODS

Construction activities

Between 2010 and 2013, 7 OWFs were constructed within the German North Sea (Fig. 1). Three OWFs were built using monopile foundations, 1 using tripile foundations, 2 using tripod foundations and 1 using jacket foundations (Table 1). One piling event was defined as a period over which piling took place without breaks longer than 3 h. For tripile, tripod and jacket foundations, several piling events could thus be defined per foundation. Table 1 gives an overview on piling-related information for all 7 wind farms in this study.

Prior to the start of piling, it is mandatory in Germany to deter marine mammals from the vicinity of the piling site to avoid physical injury. The procedure, which was followed at all wind farms in this

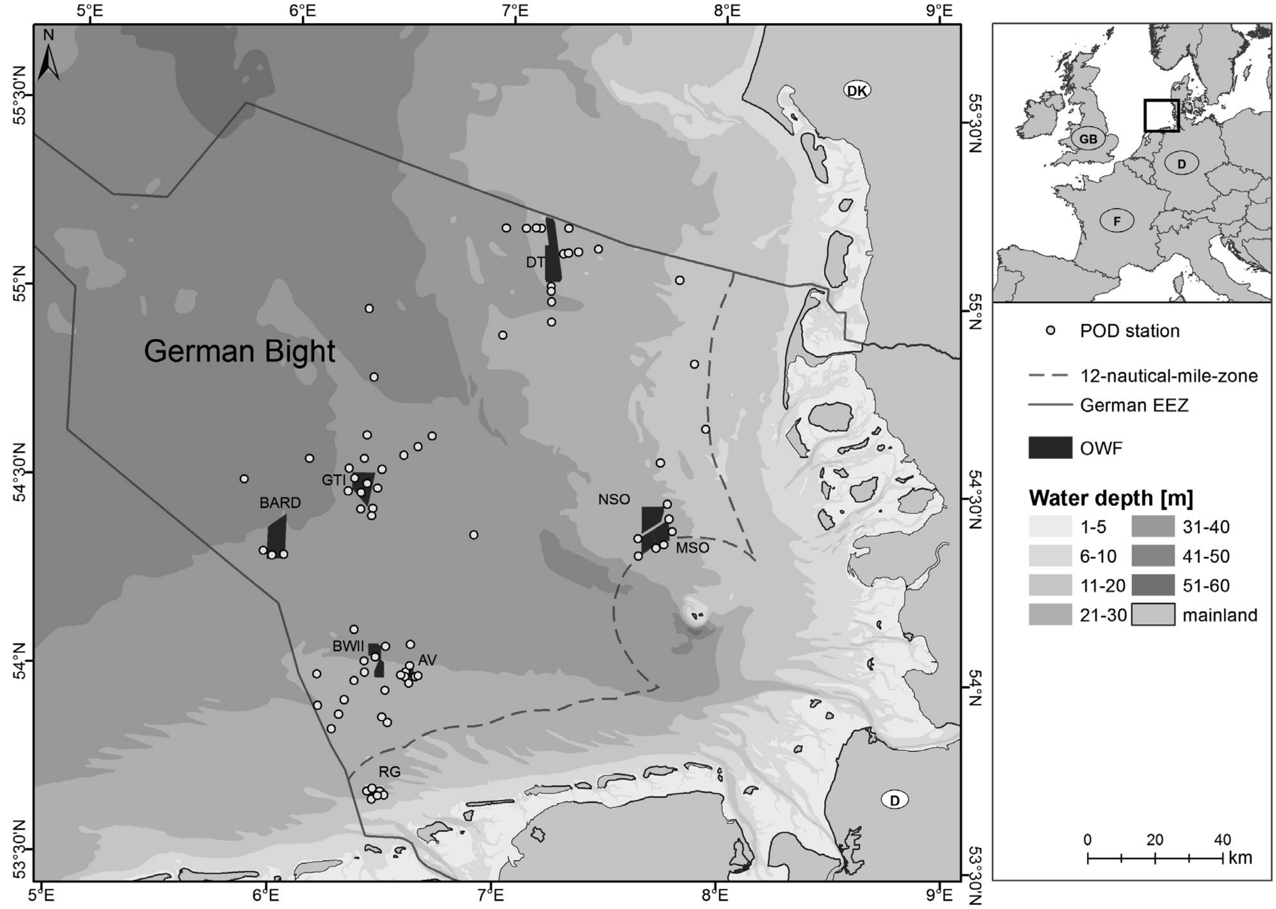

Fig. 1. Locations of stationary POD positions in this study. Offshore wind farms (OWFs) constructed until the end of 2013 within the German Exclusive Economic Zone (EEZ) are depicted as dark grey areas (DT = Dan Tysk, BARD = BARD Offshore I, BWII = Borkum West II, GTI = Global Tech I, AV = Alpha Ventus, RG = Riffgat, NSO = Nordsee Ost, MSO = Meerwind Süd/Ost). The OFW AV was a small non-commercial wind farm constructed in 2009, and was not considered in this study

study, involved the deployment of at least 1 pinger at the piling site at least 40 min before the start of piling and that of a seal scarer (either a Lofitech or an Airmar seal scarer) at least 30 min before piling. As the start of piling could not always be timed precisely, deployment of these deterrence devices was often longer, and usually a seal scarer was deployed between 30 min and 1.5 h before the start of piling. Pingers and seal scarers were to be recovered at the onset of piling.

Table 1. Project-specific characteristics of piling events occurring at the different offshore wind farms (OWF; see Fig. 1 for full names and locations) between 2010 and 2013. Noise levels are given as the mean sound exposure level exceeded during 5% of piling time (SEL_{05}) at 750 m separately for unmitigated and mitigated piling events (i.e. without and with noise mitigation systems, NMS). The number of foundations includes platforms, and the number of foundations without NMS includes those without NMS at least during part of the piling process. NA: not applicable, BBC: big bubble curtain, IHC-NMS: IHC-noise mitigation screen

OWF project	SEL_{05} without, with NMS (sample size)	Median piling duration (h)	Foundation type	No. of foundations	No. of piling events	Foundations without NMS	NMS	Water depth (m)
BARD	179 (2), NA	3.1	Tripole	81	194	80	None	39–41
BWII	173(10), 163 (28)	5.0	Tripod	41	51	11	BBC	28–33
DT	178 (2), 169 (78)	1.9	Monopile	80	86	2	BBC	21–29
GTI	176 (2), 169 (78)	8.3	Tripod	76	85	2	BBC	38–41
MSO	180 (2), 169 (76)	1.5	Monopile	81	82	2	BBC	24–27
NSO	168 (1), 166 (48)	6.2	Jacket	48	53	1	BBC	22–25
RG	NA, 163 (8)	1.0	Monopile	30	30	0	IHC-NMS	18–23

At 6 of the 7 OWFs in this study, active NMS were applied to reduce piling noise (Table 1). Here NMS refers to the application of active NMS that aim to reduce noise emission, but not deterrence or soft start, which was always applied. Only Bard Offshore I (BARD) was conducted entirely without NMS (with the exception of 2 foundations where a prototype of a small bubble curtain very close to the pile was tested). At Borkum West II (BWII), about a third of the foundations were constructed without NMS, and at all other wind farms, only 2 foundations at most were constructed without NMS, with the aim of obtaining a reference noise level to evaluate the effectiveness of the used NMS.

During 5 OWF projects, an NMS was applied in form of a big bubble curtain (BBC) produced by either of 2 different BBC-suppliers, and in the OWF project Riffgat (RG), an IHC noise mitigation screen (IHC-NMS6000) was applied. The BBC consists of a hose fitted with nozzle openings that is laid out on the sea floor around the pile at a distance of more than 50 m from the piling site. Air is fed into the nozzle hose with compressors and discharged via the nozzles. This causes a continuously rising curtain of air bubbles around the installation site, which reduces noise due to scattering and absorption effects. For the 5 mentioned OWF projects, different configurations of the BBC systems were applied. Within projects, there were differences in the number of nozzle hoses, the amount of compressed air, the distance between nozzle hose and pile and the number and size of the nozzles. The IHC-NMS6000 consists of an acoustically decoupled double-wall isolation casing with an air-filled interspace. A technical overview as well as information on the efficiency of the used NMS are given by Bellmann (2014) and Bellmann et al. (2017).

Data collection

Porpoise detection data

For this study, acoustic monitoring data for porpoises were available from 76 POD stations and 49 mobile PODs. Although stationary and mobile PODs differ in their deployment duration, the same technical device (the C-POD; Chelonia Ltd.) was used throughout to record porpoise echolocation clicks. The PODs were always located in the water column 5–10 m above the sea floor, anchored at the sea floor with a mooring system and kept in the water column using a buoy.

A C-POD is a self-contained data logger designed to detect odontocete echolocation clicks between 20 and 160 kHz. It registers click events, their time of occurrence, duration (5 µs resolution), intensity, bandwidth, frequency and envelope using digital waveform analysis (for more detail see www.chelonia.co.uk). The signals are processed in real time by a zero-crossing detector. With an algorithm included in the CPOD.exe software (version 2.0 was used during this study), these parameters are used to recognize and identify porpoise echolocation click trains. The algorithm searches for coherent click trains, which are divided into different porpoise click probability classes. In this project, the Kernel classifier version 2.0 was used. Following the recommendations of the manufacturer, only the 2 highest probability classes ('Hi' and 'Mod') were used for analyses. C-PODs were calibrated by the manufacturer for the main frequency of a harbour porpoise click (130 kHz) and standardized to the same acoustic threshold (3 dB).

A maximum of 4096 clicks min^{-1} (the so called 'scan limit') was set to be recorded to avoid memory cards exceeding their data capacity during long deployments at POD stations with a lot of background noise. If that number was reached, the POD did not record for the remaining seconds of that minute. Mobile PODs were deployed close to the piling location (usually one at 750 m and one at 1500 m) for specific piling events. This was undertaken with the aim of monitoring the effectiveness of deterrence measures according to the specific condition by the approval authorities (but which was not the subject of the present study). Each POD was usually only deployed from a few hours before to a few hours after a specific piling event. For these PODs, no scan limit was set due to their short deployment time and the need to maximise detection probability during that time. This could potentially lead to longer recording time during situations with high background noise within the frequency range of the POD (e.g. noise from wind-induced waves or boat sonar) at mobile PODs than at POD stations. High ambient noise levels may affect the performance of the detection algorithm of the C-POD software due to potential masking problems. We addressed these issues by excluding hours with more than 100 000 recorded clicks h^{-1} and with more than 2 min h^{-1} when the scan limit was reached. This led to 10.7 % data exclusion. Furthermore, we included the variable 'noise clicks' (all clicks besides identified porpoise clicks) into each model to control for its effect. This inclusion should therefore take care of potential differences in detection probabilities between mobile PODs and

POD stations. Furthermore, we ran the models without mobile PODs and did not find major differences, but including mobile PODs made the model more accurate for the near distances (0–2 km from piling) as no POD stations existed there. Fig. 1 shows the positions of POD stations.

Noise data

The noise data collected during this study consisted of outcome level statistics obtained during the construction phase of the corresponding OWF. These were in accordance with the German measurement guideline published by the Federal Maritime and Hydrographic Agency of Germany (BSH, Müller & Zerbs 2011). This means that the zero-to-peak level as well as the SEL of each single strike has to be evaluated in accordance with the ISO 18406 (2017). Background measurements were conducted prior to piling. The difference between pile driving noise and background noise at 750 m distance was always >20 dB. All measuring devices used were autonomous underwater acoustic recording units developed by itap GmbH. Anchoring systems were designed with a focus on a low self-noise and stability. The selection of suitable hydrophones was based on the expected noise emissions at the planned measuring positions and sensitivity of the hydrophones. The underwater noise measurement specification of the BSH in Germany stipulates measure positions at 750 and 1500 m from the pile and in nearby protected areas. The hydrophones were placed in the lower third of the water column, approximately 2 m above the seabed. All pile driving noise measurements at 750 and 1500 m were carried out with Reson TC 4033 hydrophones. At further remote measurement positions, with significantly lower expected noise emissions, B&K 8106 hydrophones were used due to their higher sensitivity and lower self-noise. All hydrophones were factory calibrated, and a calibration tone was recorded for each individual measurement chain to be able to calculate absolute noise levels. The used underwater noise measurement devices fulfill the requirements of the German guideline (BSH, Müller & Zerbs 2011) and ISO 18406 (2017): sampling frequency 20 Hz to 20 kHz, uncompressed data format (min 16 bit), low self-noise for the electronical part as well as for the mooring system (10 dB less than lowest signal), hydrophone sensitivity <2 dB over the frequency range and calibration interval of device every 2 yr.

For each measurement position and foundation, percentile level statistics of the complete pile driving process were produced in accordance with the German measurement guidelines: percentile statistic for SEL_{05}, SEL_{50} and SEL_{90} as well as the maximum peak level. The SEL_{90} value typically corresponds to the soft start (low used blow energy), the SEL_{50} is the medium value of all used strikes pile^{-1}, and the SEL_{05} corresponds to piling with maximum blow energy (mostly during the last phase of the piling to reach final penetration depth). Under the assumption that it is the loudest part of the piling process that mainly determines the reaction of porpoises, and because this is the percentile that German authorities require for comparison to the noise level threshold of 160 dB SEL at 750 m, we focussed on the SEL_{05} during this study. Depending on the POD position for which noise values were needed, either the measured data or the equivalent level statistics were used. These were calculated using a frequency-independent transmission loss function adapted to pile-driving noise and the measurement at 750 m. Those percentile level values served as the basis for further investigations.

Data preparation

Porpoise detection data

In order to test the short-term effects of pile driving on porpoise activity at a small spatial scale, we used the parameter 'detection positive hours' (DPH) as an indicator for porpoise activity. This parameter was used as the response variable in the following analyses. DPH describes whether or not a porpoise click-train was recorded and identified during a given hour and is thus a binary variable. These data were merged with environmental information based on geographic and time-related information, of which the ones used within the final models are listed in Table 2 together with information on resolution and data source.

As piling without NMS has previously been shown to affect porpoise detections at distances up to about 20 km (Carstensen et al. 2006, Tougaard et al. 2009, Brandt et al. 2011, Dähne et al. 2013), we decided to set a precautionary 40 km boundary around each wind farm for assessing POD data for each wind farm. This was considered a conservative limit in case effects reach further than 20 km, and was also chosen to include data from distances at which no effect was expected. This meant that single piling

Table 2. All variables used within the final generalized additive models. NMS: noise mitigation system, SSTA: sea surface temperature anomaly

Variable	Type	Description
Random variable		
POD position	Factor (many levels)	Position at which a POD was deployed (latitude/longitude)
Piling related variables		
SEL_{05}	Continuous	Noise exposure level exceeded during 5% of the piling period as measured at or extrapolated to the position of the POD
Noise mitigation	Factor (2 levels)	NMS applied or not applied
Hour relative to piling	Continuous	Hour related to work (start of a piling event or deterrence) ranging from −48 to 120 h
Distance	Continuous	Distance to a piling event in km
Piling duration	Continuous	Duration of a piling event in min
Time related variables		
HH	Continuous	Hour of the day
Day of year	Circular and continuous	Day of the year
Year	Factor (4 levels)	Year 2010 to 2013
Environmental variables		
Wind speed[a]	Continuous	Wind speed in m s^{-1}
Sediment[b]	Factor (5 levels)	Sea bed sediment (1: coarse sand with <20% mud, 2: medium coarse sand with <20% mud, 3: medium sand, 4: fine sand with <20% mud, 5: fine sand with 21–50% mud)
Wind direction[a]	Circular and continuous	Wind direction in degrees
Noise clicks	Continuous	No. of clicks recorded by POD during that hour (not including identified porpoise clicks)
SSTA[b]	Continuous	Sea surface temperature anomaly

[a]Source: NOAA High Resolution SST data provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, www.esrl.noaa.gov/psd/

[b]Source: European Marine Observation Data Network (EMODnet) Seabed Habitats project (www.emodnet-seabedhabitats.eu/) funded by the European Commission's Directorate-General for Maritime Affairs and Fisheries (DG MARE)

events could be as far as 60 km from a specific POD location, as wind farm areas are up to 20 km in diameter. The relative time of each hour to the next piling event within that particular wind farm was then determined by counting 48 h down from the start of deterrence and 120 h up from the end of piling. Each hour during which piling took place was denoted as Hour 0. Hour 1 was the first full hour without piling activities after the end of a piling event. Hours when deterrence took place but piling had not yet begun were removed from the dataset. Hours were only defined as being before a piling event (−48 to −1 h) if at least 48 h had passed since the end of the last piling event. Hours that were assigned to be before a piling event were not counted as being after a piling event. All data outside this time window of between 48 h before and 120 h after piling were excluded from analyses. In order to analyse the effects of specific piling events, we excluded data that were confounded by the effects of several piling events close in space and time. Thus, hourly data were excluded if piling took place at another wind farm <60 km away in the previous 24 h.

Noise data

Piling noise is characterised by pulses during a certain time span. The resulting impulsive noise can be described with different parameters (e.g. the absolute maximum or the energetic average values). A convenient measure for impulsive noise is the SEL. It describes the accumulated sound energy of an impulsive noise event related to 1 s and the reference pressure of 1 $\mu Pa^2 s$ (ISO 18406, 2017).

For each piling impulse, a single strike SEL can be calculated to quantify the impulsive noise event. This avoids a dependency on interpulse duration and disturbing noise sources, as this would happen with time-averaged noise levels. In order to describe an entire piling event, percentile levels are given. In this study we focussed on the SEL exceeded during 5% of the piling time (SEL_{05}).

For POD positions where no measurements were available, a sound propagation model was used to determine the noise levels at the measured distance to the sound source. The applied sound propagation model developed by itap GmbH is based on measured transmission loss data. It is suitable for impulsive pile-driving noise (Diederichs et al. 2014) and leads to a transmission loss curve shown in Fig. 2. In this figure, 3 different transmission models are plotted as lines, where the model used is denoted by the dashed black line. For comparison, the semi-empirical approach of Thiele & Schellstede (1980), which is usually used in Germany in accordance with BSH guidelines (Müller & Zerbs 2011), and a simple logarithmic transmission (15 log R) were also plotted. The simple logarithmic transmission assumes an inverse proportionality between sound pressure and the logarithm of the distance to the source. Crosses are median values of the SEL of pile-driving noise measurements from 70 m up to approximately 25 km from the sound source. The itap formula shows the best fit to the measured data. The data in Fig. 2 are based on measurements in the German North Sea at a water depth of around 40 m. All OWF projects in this study were constructed in the German North Sea at water depths between 20 and 40 m with no significant changes of water depth in the surrounding area. The sediment is sandy and medium-dense, argillaceous underground. Based on literature data (Urick 1983, Jensen et al. 2010), the influence of this range of water depth and sediment differences on the sound propagation is negligible. However, the used empirical propagation model was based on the underwater noise measurements of the projects in this study.

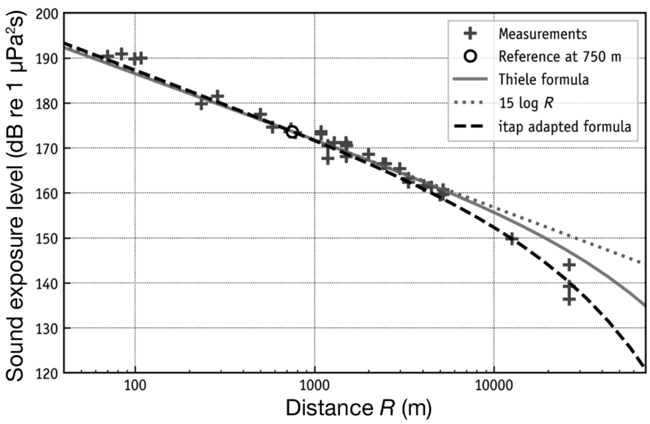

Fig. 2. Comparison of transmission models and measured sound exposure levels. The crosses denote measurements at one foundation in the offshore wind farm GTI (see Fig. 1). The circle is a reference measurement value at 750 m; it must be crossed by the transmission models curve. The gray line is a model proposed by Thiele & Schellstede (1980). A simple propagation model by assuming an inverse proportionality of the sound pressure to the logarithm of the distance to the source is displayed by the dotted line. The model proposed by itap GmbH is plotted as a dashed black line, which best fits the measurements

The computed noise values were derived by calculating the transmission loss over the distance between the measured value at a distance of 750 m to the pile and the POD position. Finally, the obtained transmission loss was subtracted from the measured value at 750 m.

Statistical analyses

Screening for temporal autocorrelation

Considering the model residuals, preliminary investigations showed that significant temporal autocorrelation originated from the DPH response variable and not from environmental covariates. Considering the statistical model definition, we determined the most parsimonious autocorrelation patterns to be taken into account in further analyses. To correct for temporal autocorrelation, we decided to use the DPH($t-1$) covariate as an auto-regressive component of the first order (Bestley et al. 2010) in our generalized additive modelling (GAM) analyses. This covariate significantly reduced the autocorrelation pattern and also allowed the use of the *bam* function, which is part of the package mgcv from the R software (R Core Team 2015). It has a faster computing time and is more flexible for statistical analyses of large datasets than the GAM function (Wood et al. 2015). The selection of the optimal model was based on Akaike's information criterion (AIC, Akaike 1974) and on a graphical investigation of the autocorrelation partial autocorrelation functions of model residuals.

Model specifications

We ran 4 different GAMs with DPH as a binary response variable. The first 3 models were very similar and only varied by the size of the dataset included and in one variable interaction term. The fourth model was based on only a small data-subset and included no interaction term.

The first model ('noise level model') addressed the question of the noise levels where porpoise detections were negatively affected by piling. It included the interaction term of SEL_{05} with hour relative to piling (HRP) to test how porpoise detections varied with time around piling depending on the noise level porpoises were exposed to. There were, however, several POD positions and piling events for which reliable noise levels could not be calculated as no measurements existed during that piling event (especially during the 2 projects BARD and RG). This substantially reduced our dataset.

The reaction of porpoises to a given noise level likely depends on the distance to the source, because several characteristics of the noise signal change with distance. This includes frequency content, fluctuations in noise level, etc., which cannot be addressed with simply the broadband noise value of SEL_{05}. However, including both distance and noise level in the same model was not possible due to high collinearity between these 2 variables. Therefore, we also ran a second model ('distance model') including the interaction term of distance with HRP as a predictor variable instead of SEL_{05} with HRP, which also enabled us to use the complete dataset. This model aimed at investigating the average effect range on harbour porpoises of all wind farm construction projects over a period of 4 yr in the German North Sea.

In order to analyse the different spatial effects of piling events with and without NMS, we ran a third model ('noise mitigation model'), which included 2 separate 2-way interaction smooths of distance with HRP for piling events with and without NMS.

In order to specifically test if piling duration was related to the strength with which porpoises were disturbed by piling, we ran a fourth model ('piling duration model') using only data collected during the first hour after the end of piling and at distances up to 5 km, so at a time and at distances where the effect of piling duration, if present, should be expected to be most pronounced.

Besides noise level and distance, day of the year and sea surface temperature were highly correlated (correlation coefficient > 0.5). We therefore only included day of the year in the 4 GAMs, as it was a better predictor of porpoise detections than sea surface temperature. For all models, POD position was included as a random effect, as it was found to (1) improve the deviance explained by the models and decrease model AIC and (2) take into account the geographical location, hence geographical-related characteristics like water depth and slope. As these 2 variables were confounded with POD position, but because POD position was a far better descriptor based on the model AIC, these 2 environmental variables were no longer used in the final models.

In addition, day of the year, hour of the day (HH), wind speed, wind direction, noise clicks, sea surface temperature anomaly (SSTA) and piling duration were included as continuous smooth functions. Year and sediment category were included as factors. DPH(t – 1) was included as a factor to correct for temporal autocorrelation as explained above. HRP with distance (or with SEL) from piling was included as an interaction term specified as a smooth function.

Non-parametric test design

In order to directly link detections during piling to a given baseline period and analyse the differences specifically for each distance class, we analysed porpoise detection rates with respect to piling effects using non-parametric tests. The noise and distance classes were based on obtaining roughly equal sample sizes within these classes and were as small as data availability allowed. Detection rates during piling were first averaged and then compared to detection rates averaged over 25–48 h before piling within the same class. Mann-Whitney U-tests were used to check for significant differences between them.

RESULTS

Noise levels during piling

At 750 m, noise levels were on average 175 ± 3.5 (SD) dB re 1 μPa^2s SEL_{05} (n = 19) during piling without NMS and 168 ± 4.6 dB re 1 μPa^2s SEL_{05} (n = 316) during piling with NMS, which gave an overall reduction in noise levels by about 7 dB. Project specific noise levels are provided in Table 1 and Fig. 3. With only one exception, median noise levels during

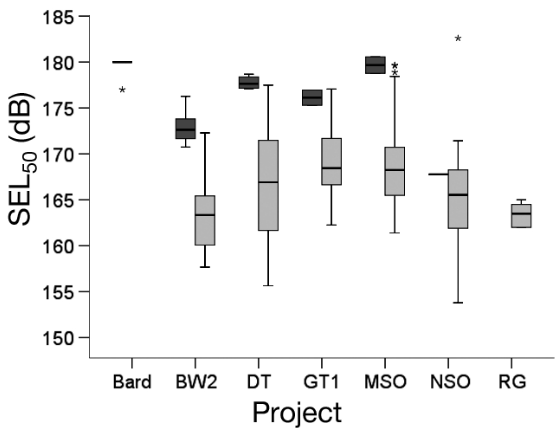

Fig. 3. Noise levels shown as the sound exposure level exceeded during 5% of piling time (SEL_{05}) without (dark grey) and with (light grey) noise mitigation systems (NMS) for the 7 different offshore wind farm projects. Note that only 2 measurements were taken at BARD, where no NMS was applied. The line represents the median, boxes 25th percentiles, whiskers 75th percentiles and asterixes indicate outliers (values more than 1.5 times the height of the boxes). See Fig. 1 for full names and locations of the wind farms

piling with NMS were substantially lower than during piling without NMS in all projects where measurements for both categories existed and decreased by between 7 and 11 dB. Only at Nordsee Ost (NSO) there was little difference between the two (about 2 dB). This was due to piling without NMS being conducted with reduced piling energy, so that piling without NMS was not as loud as it would have been had the same energy been used as during piling with NMS. Fig. 3 also shows, however, that noise levels varied substantially during piling with NMS and in some cases were as loud as during piling without NMS. It has to be borne in mind that NMS were still under development during construction of all these OWFs, with different configurations being tested.

Mean noise levels during piling with NMS did not vary much between projects compared to the variation within each project, which was due to NMS still being in the experimental phase, and consequently noise reduction was very variable also within projects. Furthermore, the German authority regulates the maximum blow energy individually per project based on soil conditions, hammer size and pile diameter.

Mean piling duration, however, was substantially longer for tripole, tripod and jacket foundations (5.4 ± 3.2 h) than for monopile foundations (1.7 ± 0.8 h), giving an overall average of 4.1 ± 3.2 h.

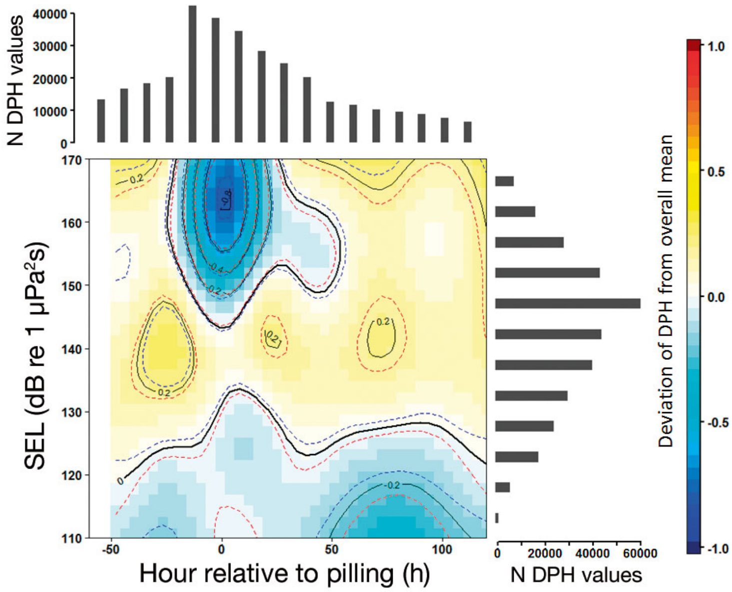

Fig. 4. Output from the 'noise model' showing the effects of the interaction of hour relative to piling with the sound exposure level exceeded during 5 % of piling time (SEL_{05}) on detection positive hours (DPH). Shown is the deviance of DPH from the global mean (bold 0-line) with cold (warm) colours indicating a negative (positive) deviation. Confidence intervals are depicted as blue and red dotted lines. Histograms indicate data availability at the different hours (−50 to −40 h, −40 to −30 h etc., according to the *x*-axis of the main figure) and SEL_{05} classes (100–105 dB, 105–110 dB etc., according to the *y*-axis)

Effect of noise level and hour relative to piling on porpoise detections

As seen in Fig. 4, showing the deviation of DPH from the overall mean of the noise level model (Table 3), DPH declined several hours before piling, was lowest during the hour when piling occurred (HRP = 0) and then increased afterwards. The lowest noise level when DPH during piling reached the overall average of all data (when a negative effect is no longer evident), was at 143 dB SEL_{05}. There was again a negative deviation from the overall mean at noise levels below 120–130 dB SEL_{05}, but this was independent of the HRP. It also needs to be kept in mind that data availability at noise levels below 130 dB SEL_{05} was rather low, as can be seen from the histograms in Fig. 4. It also appears that the strongest decline in harbour porpoise detections occurred at the loudest noise levels and effect strength gradually decreased with decreasing noise levels. As evident from the different confidence intervals, estimates were most accurate in close vicinity to piling (in space and time) and became less accurate at lower

Table 3. Results from the noise and the distance models run on the global dataset including data from all 7 wind farm projects (see Fig. 1). DPH: detection positive hours; other variables are defined in Table 2. Deviance explained: 6.8 % for the noise model and 7.4 % for the distance model; in all cases, $p < 0.001$; –: variable not included

Variable	Noise model (e)df	Noise model Chi^2	Distance model (e)df	Distance model Chi^2
DPH($t-1$)	1	337	1	499
POD position (random factor)	219	7891	445.8	12393
Year (factor)	3	778	3	1134
Day of year (smooth)	8.0	8586	8.0	15882
HH (smooth)	7.0	909	7.1	1015
Wind speed (smooth)	8.0	2053	8.3	3007
Wind direction (smooth)	6.5	131	7.2	448
SSTA (smooth)	8.7	764	8.7	874
Noise clicks (smooth)	6.1	1687	7.7	2118
Sediment (factor)	4	21	4	36
Piling duration (smooth)	8.9	583	8.9	625
Hour relative to piling, distance (interaction)	–	–	28.4	2535
Hour relative to piling, $SE0_{05}$ (interaction)	28.4	2204	–	–

noise levels and as more time since piling had passed. There was also a tendency for decreases in porpoise detections to last longer at louder noise levels. The noise level model explained 6.8% of deviance, and the interaction SEL_{05} with HRP was significant ($p < 0.001$, Table 3).

Effect of distance and hour relative to piling on porpoise detections

Similarly to results from the noise level model, the distance model (Table 3) showed that porpoise detections at the closest distances to piling started to decline several hours before the start of piling, reaching a minimum during piling (HRP = 0) and increased afterwards (Fig. 5). The distance model explained 7.4% of deviance, and the interaction of distance with HRP was significant ($p < 0.001$, Table 3). During piling, porpoise detections were below the overall average up to 17 km from piling, after which a very clear change in detection rates was found around the time of piling (Fig. 5). Detection rates were below the overall average at distances further than about 40–50 km, but this was unrelated to the times of piling and represented a more general pattern in porpoise occurrence. The gradient in effect strength was much clearer than in the noise level model. The decrease in porpoise detections was strongest in the direct vicinity to piling but gradually decreased with distance to piling. This is also the case for effect duration; Fig. 5 shows that porpoise detections were below the overall average for a much longer period in close vicinity to piling than at further distances, both before and after piling.

In order to investigate how NMS altered the effects of piling on harbour porpoise detections, NMS was added as an additional factor with 2 levels ('yes' and 'no') within the distance model, resulting in the noise mitigation model (Table 4). NMS was included as a third variable into the interaction of distance with HRP, which slightly improved the model (ΔAIC = 380.2, 7.52% as opposed to 7.44% deviance explained), and the 3-way interaction term (HRP, distance, NMS) was significant ($p < 0.001$, Table 4). Looking at deviations of DPH values from the overall average during piling, DPH reached the

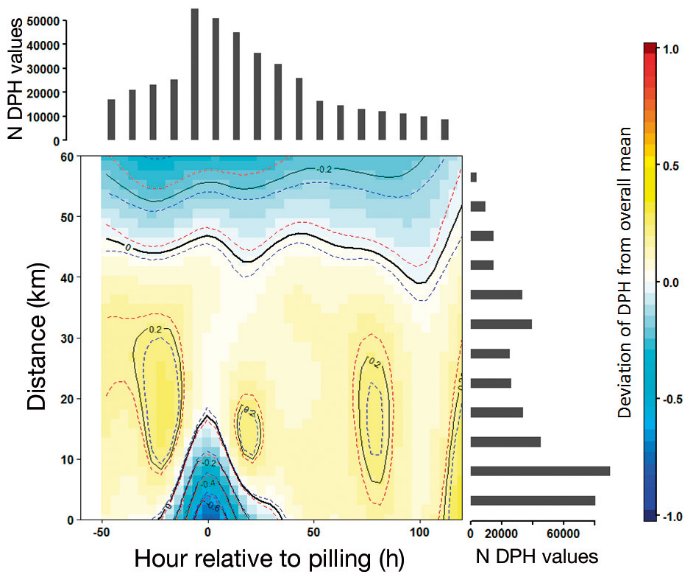

Fig. 5. Output from the 'distance model' showing the effects of the interaction of hour relative to piling with distance to the piling location (in km) on detection positive hours (DPH). Shown is the deviance of DPH from the global mean (bold 0-line) with cold (warm) colours indicating a negative (positive) deviation. Histograms indicate data availability at the different hour classes (−50 to −40 h, −40 to −30 h, etc., according to the *x*-axis of the main figure) and distance classes (0–5 km, 5–10 km etc., according to the *y*-axis)

Table 4. Results from the noise mitigation model run to check for the effects of noise mitigation on effect ranges of piling and the piling duration model run to specifically look at the effects of piling duration. DPH: detection positive hours; other variables are defined in Table 2. Deviance explained: 7.5% for the noise mitigation model and 15.2% for the piling duration model. ***p < 0.001, ns: not significant, –: variable not included

Variable	Noise mitigation model (e)df	Chi^2	p	Piling duration model (e)df	Chi^2	p
DPH(t−1) (factor)	1	483.4	***	1	0.1	ns
POD position (random factor)	448.8	12246	***	<1	43	**
Year (factor)	3	1136	***	3	8	ns
Day of year (smooth)	8.0	14541	***	6	43	***
HH (smooth)	7.1	980	***	<1	0	ns
Wind speed (smooth)	8.3	2878	***	1	15	***
Wind direction (smooth)	7.3	370	***	<1	0	ns
SSTA (smooth)	8.7	892	***	1	3	ns
Noise clicks (smooth)	7.7	2043	***	2	6	ns
Sediment (factor)	4	35	***	4	4	ns
Piling duration (smooth)	8.9	664	***	2	1	ns
Distance (smooth)	–	–	–	1	15	***
Hour relative to piling, distance, for noise mitigation=no (interaction)	28.1	1153	***	–	–	–
Hour relative to piling, distance, for noise mitigation=yes (interaction)	28.0	1701	***	–	–	–

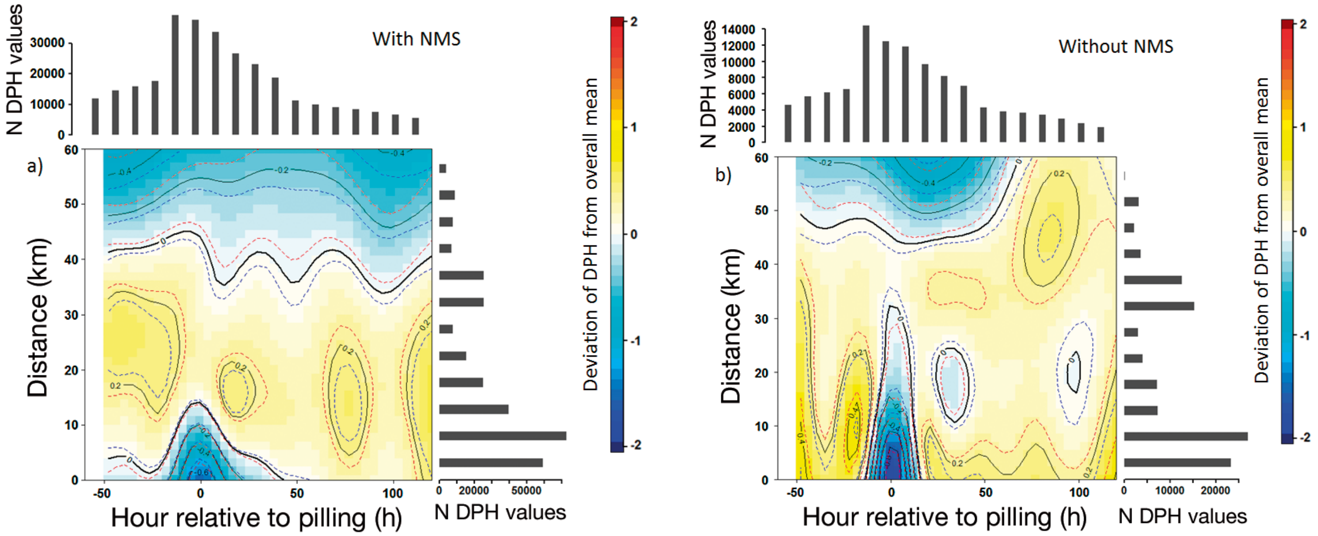

Fig. 6. Output from the 'noise mitigation model' showing the effects of the interaction of hour relative to piling with distance to the piling location (in km) on detection positive hours (DPH) for piling events (a) with noise mitigation systems (NMS) and (b) without NMS. Shown is the predicted deviation of DPH from the overall mean, with cold (warm) colours indicating a negative (positive) deviation. Histograms indicate data availability at the different hour classes (−50 to −40 h, −40 to −30 h, etc., according to the *x*-axis of the main figure) and distance classes (0–5 km, 5–10 km etc., according to the *y*-axis) of the specific POD position

overall average at about 14 km from piling for piling events with NMS (Fig. 6a). For piling events without NMS, the estimated effect ranges were less clear due to a more complicated pattern of the 0-isocline (indicating the overall average) and broader confidence intervals around the isocline due to relatively low data availability at these distances. The global average during piling was reached at 33 km, but detection rates during piling did not differ much between 17 and 33 km, showing that there is no well-defined limit for effect ranges resulting from this model. Instead, an effect range of somewhere between 17 and 33 km may be assumed (Fig. 6b).

For piling events with and without NMS, the decline in porpoise detections started several hours before piling and lasted several hours after piling at close ranges. There seems to be a tendency, however, for a longer lasting effect in the vicinity of piling during piling events that applied NMS.

Fig. 7 presents the raw data for DPH at the different hours relative to piling for distances between 0 and 5 km. While there was a clear decrease in DPH several hours before piling, there was a further pronounced decrease from the hour before piling to the hour of piling. When comparing porpoise detections during the hour directly before piling (0.3) to the average 25–48 h before piling (0.47), there was a decrease of about 36% over 24 h. Comparing mean DPH during piling (0.15) to the hour directly before piling (0.3), there was a decrease of about 50% over a period of about 1 h, and compared to 25–48 h before piling, there was an overall decrease of about 68%. Thus, although there was a considerable decline in porpoise detections before piling, the strongest decline happened while piling was taking place. Tables 5 & 6 present average DPH values at different times before, during and after piling, separated for different distance classes and for piling events with and without NMS. Results from non-parametric *U*-tests are provided in Tables 5 & 6. Fig. 8 illustrates how much DPH declined during piling with and without NMS at different distance classes. Independent of whether or not NMS were applied, statistically significant declines occurred up to 10–15 km from the piling site (when compared to 25–48 h before and to 25–48 h after piling) but not beyond. However, the decline in

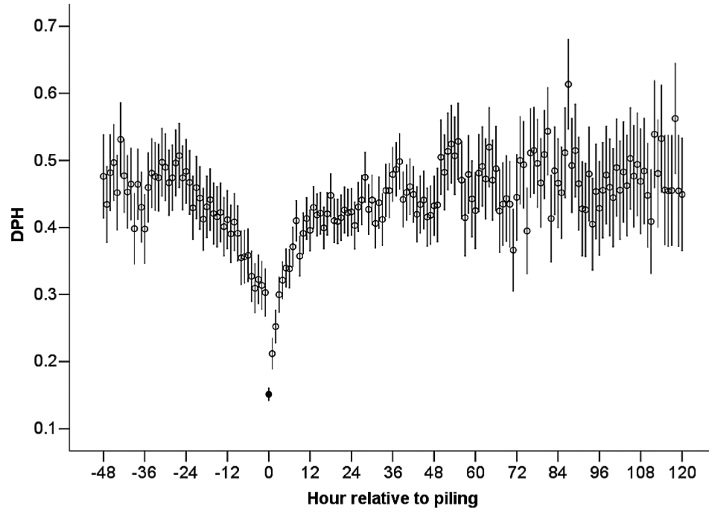

Fig. 7. Mean and 95% confidence intervals of detection positive hours (DPH) at the different hours relative to piling for distances between 0 and 5 km. The hour relative to piling = 0 is indicated as a filled black circle

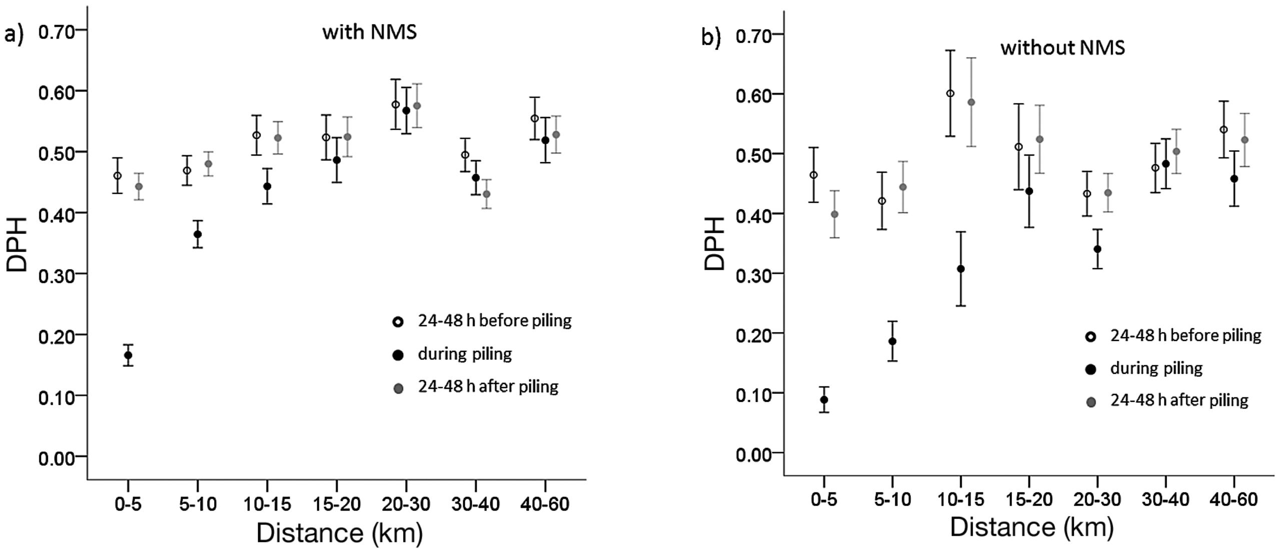

Fig. 8. Mean and 95% confidence intervals of detection positive hours (DPH) at different distance classes to piling for the baseline periods 48–25 h before piling (black error bars with open circles), during piling (black bars with filled circles) and for 25–48 h after piling (grey error bars with grey filled circles) for piling events (a) with noise mitigation systems (NMS) and (b) without NMS

DPH during piling events without NMS was much stronger than when NMS were applied. Without NMS, porpoise detection during piling declined by more than 50% in the 10–15 km distance class, but by only 17% during piling events with NMS. Regardless of whether NMS were applied, the spatial gradient in effect strength was obvious in both cases (Fig. 8).

Effect of piling duration on porpoise detections

It may be expected that the duration of a piling event would have a negative effect on DPH, as animals may swim further away from the noise source if disturbance continues for a longer time period.

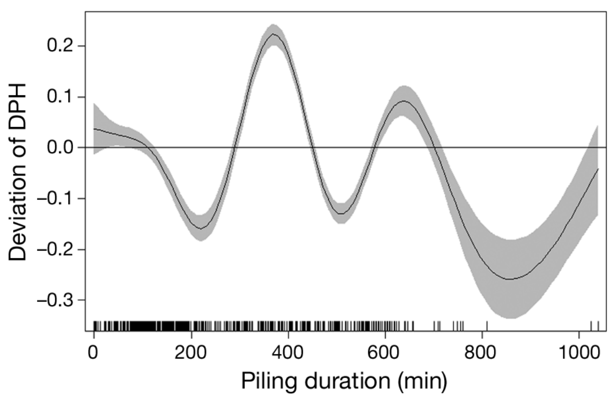

Fig. 9. Output from the distance model showing the effects of piling duration (in min) on detection positive hours (DPH). Shown is the predicted deviation from the overall mean, including confidence intervals (grey shaded areas). Black tick marks indicate data availability

Therefore, piling duration was incorporated into each statistical model and had a significant effect in all models. However, the relationship was not linear (Fig. 9). While DPH clearly decreased with increasing piling duration, up to about 200 min of piling, DPH also showed positive and negative deviations during longer-lasting events. Finally, the piling duration model did not show any significant effect of piling duration ($p > 0.05$, Table 4).

DISCUSSION

Many OWFs have been built in Northern European waters over the last decade, and there are plans for many more worldwide. As noise levels during pile driving may induce hearing impairments in harbour porpoises at close range and cause disturbance and displacements over considerable distances, concern has been expressed that this could lead to impacts on their populations.

In the EU, all countries are obliged to maintain or achieve a favourable conservation status of strictly protected species including all cetaceans, and the EU habitats directive prohibits any disturbance that might negatively affect the conservation status of strictly protected species within specific areas ('local population').

Consequently, all countries active in offshore wind energy developments in the EU have adopted some measures to avoid hearing impairment in harbour porpoises. While the use of deterrents is practiced in

Table 5. Average values for detection positive hours (DPH, sample size in brackets) calculated over the global dataset for 5 different time classes (HRP: hour relative to piling) and 6 different distance classes for piling events with noise mitigation. Also given is the percentage decline in DPH at the hour of piling relative to the 25–48 h time period before the start of piling and significance levels from a Mann-Whitney *U*-test, testing differences between DPH at 25–48 h before piling to DPH during piling (test 1) and between DPH during piling to 25–48 h after piling (test 2). ***p < 0.001, *p ≤ 0,05, ns: p > 0.05

Distance class (km)	HRP –48 to –25	HRP –24 to –1	HRP 0	Significance 1 to 24	Significance 25 to 48	DPH decline (%)	Test 1	Test 2
0–5	0.46 (348)	0.36 (565)	0.17 (1012)	0.35 (1168)	0.44 (705)	63	***	***
5–10	0.47 (472)	0.41 (946)	0.37 (946)	0.46 (1033)	0.48 (796)	21	***	***
10–15	0.53 (265)	0.48 (307)	0.44 (579)	0.50 (622)	0.52 (399)	17	***	***
15–20	0.53 (166)	0.49 (187)	0.49 (347)	0.52 (364)	0.53 (253)	8	ns	ns
20–30	0.58 (147)	0.56 (185)	0.58 (334)	0.54 (365)	0.58 (245)	0	ns	ns
30–40	0.50 (335)	0.46 (367)	0.46 (646)	0.44 (670)	0.43 (539)	8	*	ns
40–60	0.56 (173)	0.53 (213)	0.52 (353)	0.51 (398)	0.53 (277)	7	ns	ns

Table 6. As in Table 5, but for piling events without noise mitigation

Distance class (km)	HRP –48 to –25	HRP –24 to –1	HRP 0	Significance 1 to 24	Significance 25 to 48	DPH decline (%)	Test 1	Test 2
0–5	0.62 (34)	0.46 (65)	0.12 (87)	0.47 (98)	0.51 (71)	81	***	***
5–10	0.53 (52)	0.49 (83)	0.25 (110)	0.39 (118)	0.56 (71)	53	***	***
10–15	0.63 (43)	0.56 (61)	0.31 (87)	0.48 (97)	0.64 (55)	51	***	***
15–20	0.62 (30)	0.65 (36)	0.51 (50)	0.63 (52)	0.67 (33)	18	ns	*
20–30	0.72 (10)	0.66 (16)	0.55 (25)	0.71 (23)	0.70 (16)	24	ns	ns
30–40	0.58 (24)	0.48 (26)	0.64 (37)	0.59 (36)	0.68 (27)	+10	ns	ns
40–60	0.46 (19)	0.45 (28)	0.46 (44)	0.49 (46)	0.53 (27)	0	ns	ns

all of these countries, only few require active noise mitigation when a certain noise threshold is exceeded. To be able to assess whether OWF construction could compromise the conservation status of harbour porpoises and to decide if regulations are necessary, knowledge on how harbour porpoises respond to pile driving and the usefulness of the application of NMS is essential.

We analysed the spatial and temporal avoidance reactions of harbour porpoises to pile driving during construction of the first 7 large-scale OWF in the German North Sea, the majority of which were constructed using NMS. We consider this information to be useful for regulators and the scientific community facilitating assessments of potential population-level consequences when using population simulation models such as the 'interim population consequences of disturbance' model (iPCoD, King et al. 2015) or the 'disturbance effects on the harbour porpoise population in the North Sea' model (DEPONS, Nabe-Nielsen et al. 2018). Both models aim to predict population-level consequences of offshore construction activities on marine mammals but use different approaches. The main difference is that DEPONS uses individual-based/agent-based modelling, where an animal's survival is an outcome of the individual's ability to find food, and it allows for individual animals to be affected to different degrees depending on noise level. On the other hand, iPCoD uses average survival rates for the specific region and does not allow animals to be affected to different degrees (Nabe-Nielsen & Harwood 2016). While DEPONS is parameterised based on empirical observations, iPCoD uses an expert elicitation process to assess the fitness consequences of behavioural changes. Both models require knowledge about the noise level or distance where animals start to be disturbed by an offshore activity, and this is where our study may help to provide realistic estimates for the effects of offshore piling with and without NMS being applied.

Effects of noise levels

For environmental impact assessments based on noise predictions, it is of particular interest to establish the relationship between noise levels from offshore pile driving and porpoise responses. Therefore, one aim of this study was to establish the noise levels at which changes were found in hourly porpoise detection rates. GAMs revealed clear declines in acoustic porpoise detections at noise levels exceeding an SEL_{05} of 143 dB re 1 µPa^{2}s. This estimate was based on the noise level where porpoise detections during piling reached the overall mean of all data. It needs to be kept in mind that this average is calculated over all available data, and this also includes impact data. As such, 143 dB re 1 µPa^{2}s could be an underestimation for a threshold level. However, at louder noise levels, the model no longer showed a clear change in porpoise detections with time relative to piling, which supports the idea that taking the overall average represented a relatively 'normal' level of porpoise detections.

Dähne et al. (2013) also studied the effect of piling on porpoise acoustic detections and sighting rates in the field, but only gave a very broad estimate of the noise levels that led to displacement, which lay between SELs of 139 and 152 dB re 1 µPa^{2}s. The 143 dB (SEL_{05}), estimated for the onset of avoidance behaviour during this study, falls within this range but provides a more specific estimate. Our data also indicated that porpoises probably did not show an 'all-or-nothing' response, as the higher the noise levels were over 143 dB, the stronger was the decline in porpoise detections.

During a study of captive animals, Kastelein et al. (2013) observed a significant increase in jumping frequency of a harbour porpoise exposed to playback noise of pile driving at a single strike SEL of 145 dB re 1 µPa^{2}s. Respiration rate increased at 127 dB re 1 µPa^{2}s, while no difference could be found regarding distance of the animal to the transducer until 145 dB re 1 µPa^{2}s (the loudest noise level tested). A more recent analyses of these data revealed, however, that the porpoise already increased swimming speed at the lowest tested noise level of 121 dB re 1 µPa^{2}s (Kastelein et al. 2018). This may illustrate the difficulties when comparing results from the field to those found in captivity. While studies of captive animals can focus on small individual changes in behaviour, such as respiration rate (which is extremely difficult to study in the field), it is difficult to find out at what threshold animals will start to avoid a noise source (which is what is usually studied in the field). Animals in captivity are constrained in their avoidance behaviour, and noise characteristics in a pool may not offer sufficient variation for an animal to be able to move to a quieter area and thus differ substantially from what is usually found in the field. Thus, measuring the effects of noise on individual behavioural changes of porpoises in captivity, or on porpoise detection rates in the field, simply represent 2 different approaches. These results are not expected to be directly comparable. Thus, it is actually surprising that the 2 levels of 145 dB re 1 µPa^{2}s (at which porpoises showed increased jumping frequency in the pool) and 143 dB re 1 µPa^{2}s (at which we found porpoise detection rates to decrease) are so similar. This could support the assumption that porpoises in the pool (where avoiding a noise source is not possible) start to jump at noise levels that in the field would lead to them swimming away from the noise source.

Piling noise has the greatest energy at relatively low frequencies, below 1 kHz. Noise from other activities with different frequency spectra will naturally yield different estimates for the onset of behavioural reactions. Seal scarer noise, for example, is emitted at higher frequencies, of about 15 kHz, where porpoise hearing is more sensitive (Kastelein et al. 2002). Accordingly, avoidance behaviour by harbour porpoises to seal scarer noise is induced at much lower noise levels of about 119 dB SEL (Brandt et al. 2013a). Tougaard et al. (2015) reviewed the available literature to assess frequency-specific responses of harbour porpoises to noise and suggested that behavioural reactions of porpoises are usually found at about 40–50 dB above the frequency-specific hearing threshold. NMS may have altered the frequency spectrum of piling noise when compared to unmitigated piling noise, as there is evidence that bubble curtains dampen high-frequency components of noise more effectively than lower-frequency components (Würsig et al. 2000, Lucke et al. 2011, Dähne et al. 2017), and thus the frequency content of noise measurements may be considered in more detail during future projects.

Effect ranges and effects of NMS

Further analyses, looking at the distances over which we found porpoise detections to change in response to piling, revealed clear declines up to 17 km when analysing all piling events jointly, regardless of whether or not NMS were applied. The strength of this decline was greatest and longest at the closest distances. We think that this gradient is a result of more animals reacting, or animals responding more strongly, or quickly, to noise when it is louder and/or when the noise source is closer. Inter-individual differences in behavioural avoidance thresholds are expected, as an animal's reaction to a stimulus may vary depending on its age, experience, nutritional state, reproductive state, current behaviour and other factors. The gradient in effect strength could also simply be a result of animals exposed to noise in the vicinity of piling not having had sufficient time to leave the disturbed area. Assuming a maximum swim speed of 4.3 m s^{-1}, as found by Otani et al. (2001), porpoises would be able to completely leave the 17 km radius, over which we found effects when considering all data, in about 1.1 h. Brandt et al. (2013a) found that porpoises swim away from a seal scarer at an average speed of 1.6 m s^{-1}, and Kastelein et al. (2018) found a porpoise to increase its mean swim speed to 2 m s^{-1} when exposed to piling noise of 145 dB re 1 µPa^2s without a decline in swim speed during the 30 min trial. Using these estimates, a porpoise would need between 2.4 and 3 h to leave this 17 km radius. All of these estimates are below the average duration found for piling events during this study, which was 4.1 h ± 3.2 h. This is sufficient time for porpoises to completely leave the impacted area, although piling duration was very different between monopile foundations (1.7 ± 0.8 h) and tripole, tripod and jacket foundations (5.4 ± 3.2 h). There is, however, a 30 min deterrence period before each piling event, which also needs to be taken into account.

Furthermore, we found no consistent effect of piling duration on porpoise detections, contrary to our expectations that longer piling duration would lead to stronger declines. This should be expected if the gradient found in effect strength was caused by animals not yet having had enough time to leave the impacted area. It has to be considered, however, that piling was not continuously ongoing during these periods. Thus, porpoises may not continuously move away during piling. However, we found that piling with NMS led to a markedly lower decline in porpoise detections within the 0–5 km radius than piling without NMS, which would not be expected if the gradient in effect strength was solely due to animals not yet having had enough time to leave. Dähne et al. (2013) described an effect of piling duration on the time between 2 porpoise encounters during their study, but their calculations of time between porpoise encounters included the time during piling. Therefore, the effect could simply stem from animals avoiding the impacted area during the period of piling, and it does not necessarily mean that they swam further away when piling lasted longer, or that it took longer for them to return. Even though our results suggest that porpoises respond at different noise levels, as also reported by Brandt et al. (2013a), the exact reasons for the gradient in effect strength cannot clearly be identified, and there may be several effects playing a role, such as inter-individual differences, the animals' behavioural states, profitability of foraging patches, etc.

Noise levels during piling with NMS were between 7 and 11 dB lower than during piling without NMS. However, noise levels during noise-mitigated piling were very variable and during some piling events as loud as during piling without NMS. This was due to NMS still being under development during the time of this study. Throughout the construction period, several configurations of NMS were tested, developed and improved. Consequently, the efficiency of noise mitigation was very variable and probably also depended on weather-related phenomena. Nevertheless, the application of NMS altered the effects of piling on porpoise detections: from GAM analyses, effects were evident up to 14 km during piling with NMS, while without NMS they ranged between 17 and 33 km. Furthermore, at all distances, porpoise detections decreased with greater strength when no NMS were applied. Non-parametric analyses, for which distance groups had to be created, revealed porpoise detections to significantly decline at up to 10–15 km distance from piling but not beyond. However, declines at 10–15 km were only 15% with NMS, but 48% without. Thus, effect strength during piling with NMS was reduced considerably, which was likely due to a lower percentage of animals reacting with avoidance behaviour when noise was reduced.

Nehls et al. (2016) calculated effect ranges to decrease by about 10 km (and thereby reduce the disturbed area by up to 90%) if the application of NMS caused a reduction of between 9 and 13 dB SEL_{50}. The reduction in effect range that we found was of considerably smaller magnitude. This may be partly explained by the high variance in noise levels during piling with NMS. Furthermore, effect ranges during piling without NMS could not be defined very accurately, because of relatively low sample size, especially at the critical distances. Even though non-parametric tests revealed significant declines during piling without NMS at distances up to 10–15 km, results from GAMs suggested effect ranges of between 17 and 33 km. Previous studies of the effect of piling without NMS, however, also found negative effects between 15 and 20 km: Carstensen et al. (2006) found effects up to 15 km in the Danish Baltic Sea, and Tougaard et al. (2009) found effects up to at least 20 km in the Danish North Sea, but both did not consider distances beyond 15 and 20 km, respectively. Brandt et al. (2011) found negative effects up to 19 km but increased porpoise detection rates at 21 km in the Danish North Sea, and Dähne et al.

(2013) found negative effects up to about 20 km with increased detection rates at 25 and 50 km in the German North Sea. Another factor that may play a role in determining avoidance radii is the deployment of seal scarers both before unmitigated and mitigated piling. The seal scarer could potentially have further reaching effects on porpoises than piling with NMS, and Brandt et al. (2013b) found significant effects of a seal scarer up to at least 7.5 km when deployed in the North Sea, where SEL levels of the seal scarer were about 113 dB SEL. On the other hand, visual observations of porpoise behaviour, in conjunction with noise measurements, revealed that porpoises started to avoid seal scarer noise at noise levels of about 119 dB SEL, but not at lower noise levels (Brandt et al. 2013a). Therefore, an effect reaching up to 15 km would be unlikely. Under the current construction scenario, where mitigated piling noise is always accompanied by prior seal scarer deployment, these 2 sources of disturbance cannot be separated. However, it would be important to look into this in the future, in order to avoid seal scarer noise causing unnecessary disturbance and actually limit the positive effect of the application of NMS.

Different deterrence devices, where the source level can be adapted and that emit signals at higher frequencies, could provide better alternatives. One such example is the FaunaGuard, for which different modules allow targeting of specific species (such as seals or porpoises) and that can be tuned to the project-specific deterrence ranges needed (Kastelein et al. 2017). Especially in the future, when NMS are expected to work more efficiently and thus lead to even smaller danger zones and smaller avoidance distances, it will be crucial to also change the current deterrence procedure in order to keep overall deterrence effects by OWF construction at the achievable minimum.

Another factor that complicates the assessment of effect ranges may be an interacting effect of distance with noise. This could come from animals having some additional clues that provide information on the distance over which sound has travelled. The frequency spectrum, for example, is known to change with distance (Hermannsen et al. 2015) and so will the fluctuations of noise levels, and the duration of an impulse. This may raise the question of whether the unit in which noise was measured is adequate for assessing porpoise responses. It will, however, always be difficult to find a unit that encompasses all parameters that potentially lead to a different perception of given noise levels by porpoises. In this case, noise measurements were not detailed enough to also assess how frequency content and time-specific details of noise changed over distance, such that using broadband sound exposure levels, and also analysing the effect of distance, was the best we could do with the available data. Thus, animals may have reacted more strongly to a given noise level if they were exposed to it at a shorter distance from piling than when exposed to it further from piling. Moreover, there may be a difference in the noise levels at which animals continue to swim away, depending on sound level at first exposure due to potential habituation effects. Next to NMS having worked to varying degrees, all of these factors may contribute to a blurred picture when comparing effects with and without NMS based on field data, and consequently, effect ranges between piling with and without NMS do not appear to differ to the extent originally expected.

Effects before piling

Porpoise detections in the vicinity of the construction site started to decline several hours before piling, although not to the extent found during piling. The most likely explanation, in our opinion, is an increase in construction-related activities, such as an increase in shipping traffic in combination with enhanced sound transmission during the calm weather conditions during which piling activities occur (Dragon et al. 2016). This could contribute to porpoise deterrence, and a recent study suggests that porpoises may react to shipping activity at distances over 1 km (Dyndo et al. 2015). Effect duration in the vicinity of piling tended to be longer for piling events with NMS than for piling events without NMS, and this could be related to more shipping activity associated with noise-mitigated piling events when NMS have to be installed and uninstalled. This poses the question as to how much of the effect duration after piling is really due to ongoing deterrence effects from piling noise and how much may be caused by other construction- and weather-related noise characteristics. It also poses the question if by using NMS, one trades a smaller effect radius and a smaller effect strength for a longer effect duration in the vicinity of the construction site. As we lack sufficiently detailed information on shipping activity in relation to piling, we are currently unable to shed more light on this issue, but this is certainly an interesting aspect to be considered in future studies.

Nevertheless, by using NMS, the effect on porpoises was clearly reduced in terms of effect strength and also effect range. Within these projects, NMS have successfully been used in water depth up to about 40 m, but in the future, applications at greater water depth should also be possible. However, here a combination of different types of NMS may be necessary. NMS have undergone great improvement since 2013. During wind farm construction projects after 2013, noise levels at 750 m distance usually fell below the threshold limit of 160 dB (I. Buescher, BSH, pers. comm.). Therefore, a further reduction of the disturbance effects should also be expected, and future studies may determine if this expectation is met, and whether porpoise populations have changed over the years of construction. In the meantime, a serious discussion is needed about the level of disturbance that is acceptable from a biological point of view and whether the reduction in disturbance effects, which can be achieved by further noise mitigation, justifies the increased costs required (the application of NMS makes up about 15% of the total costs of the installation process of turbine foundations). Furthermore, the seriousness of disturbance of a piling event will critically depend on the alternatives that are available to porpoises at that time, and thus spatial and temporal planning of simultaneous construction activities within the North Sea seem just as important as noise mitigation efforts.

CONCLUSIONS

This study identified a noise threshold level of 143 dB SEL_{05} above which harbour porpoises reacted with avoidance to pile driving during OWF construction. It also quantified the amplitude as well as the spatial and temporal extent of disturbance and showed that the application of NMS led to a clear reduction in amplitude, and a slight reduction in the spatial but not in the temporal extent. This information may be used to more accurately quantify disturbance effects within population models in order to predict population level consequences of the construction of marine renewable energy projects on harbour porpoises.

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