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Effects of pile-driving on harbour porpoises (*Phocoena phocoena*) at the first offshore wind farm in Germany

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Abstract
The first offshore wind farm 'alpha ventus' in the German North Sea was constructed north east of Borkum Reef Ground approximately 45 km north off the German coast in 2008 and 2009 using percussive piling for the foundations of 12 wind turbines. Visual monitoring of harbour porpoises was conducted prior to as well as during construction and operation by means of 15 aerial line transect distance sampling surveys, from 2008 to 2010. Static acoustic monitoring (SAM) with echolocation click loggers at 12 positions was performed additionally from 2008 to 2011. SAM devices were deployed between 1 and 50 km from the centre of the wind farm. During aerial surveys, 18 600 km of transect lines were covered in two survey areas (10 934 and 11 824 km^2) and 1392 harbour porpoise sightings were recorded. Lowest densities were documented during the construction period in 2009. The spatial distribution pattern recorded on two aerial surveys three weeks before and exactly during pile-driving points towards a strong avoidance response within 20 km distance of the noise source. Generalized additive modelling of SAM data showed a negative impact of pile-driving on relative porpoise detection rates at eight positions at distances less than 10.8 km. Increased detection rates were found at two positions at 25 and 50 km distance suggesting that porpoises were displaced towards these positions. A pile-driving related behavioural reaction could thus be detected using SAM at a much larger distance than a pure avoidance radius would suggest. The first *waiting time* (interval between porpoise detections of at least 10 min), after piling started, increased with longer piling durations. A gradient in avoidance, a gradual fading of the avoidance reaction with increasing distance from the piling site, is hence most probably a product of an incomplete displacement during shorter piling events.

Keywords: underwater noise effects, pile-driving, harbour porpoise, behavioural reactions, offshore wind farm, static acoustic monitoring, C-PODs, aerial surveys, North Sea

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1. Introduction

The German offshore wind power production is supposed to expand to a nominal capacity of 25 GW until 2030 (BMWI 2012). This German energy policy has been developed over the last years, but was strengthened after the 2011 catastrophe at the Fukushima Daichi nuclear power plant allowing German nuclear power plants to be shut down and decommissioned until 2022.[6] The development of offshore wind energy is thought to play a major role within the shift of the energy mix towards renewable energies with emphasis on wind energy in general[7]. In Denmark, The Netherlands, Belgium and the UK a large number of offshore wind farms are planned or are already in operation (Breton and Moe 2009, KMPG 2010).

The first offshore wind farm in the German North Sea, the 'alpha ventus' (AV) test site was installed off the island of Borkum in the southern German Bight in 2008 and 2009. The construction and operation of this wind farm, with 12 turbines of a rated power of five MW each, was accompanied by a large number of applied research projects (RAVE—Research at Alpha VEntus) targeting operation, coordination, measurement engineering, foundation and main frame structure, systems engineering and monitoring, energy grid integration as well as ecology and safety. Ecological research focused on developing new methods, testing noise mitigation measures and evaluating the regulatory framework for conducting environmental impact assessments (EIAs), the so-called StUK 3 (Standard—Investigation of the impacts of offshore wind turbines on the marine environment, version 3; BSH 2007) of the permitting agency (German Federal Maritime and Hydrographic Agency, BSH). To evaluate whether these requirements were appropriate and lead to scientifically sound results, a comprehensive research study was conducted even at a larger scale than required by the StUK 3 and by using a wider set of methods (e.g. Krägefsky and Krone 2012, Reichert *et al* 2012).

A key species in this context is the harbour porpoise (*Phocoena phocoena*), the only resident cetacean species in German waters (Siebert *et al* 2006, Gilles *et al* 2009). Being distributed in coastal waters of the temperate northern hemisphere, the harbour porpoise is particularly vulnerable with respect to disturbance, injury, or death from anthropogenic activities, including by-catch in fisheries, prey depletion, noise (e.g. from the installation and operation of marine energy facilities), vessel traffic or habitat degradation due to chemical pollution (e.g. Siebert *et al* 1999, DeMaster *et al* 2001, Wünschmann *et al* 2001, Beineke *et al* 2005, Das *et al* 2006, Herr *et al* 2009). The most significant threat to marine mammals from offshore wind energy is most probably pile-driving impact noise (Madsen *et al* 2006). Hydraulic pile-driving was used to install the pile foundations for the 12 wind turbines and the transformer platform at AV. With each impact of the hydraulic hammer some of the energy exerted on the pile is transmitted into the water column and the seabed as an unintended by-product.

Due to the complex nature of the sound field created by a steel pile during pile-driving in shallow water (Reinhall and Dahl 2011), the source level is not an appropriate measure (Zampolli *et al* 2013), although it has been used in the past (Bailey *et al* 2010). The measured levels in different distances from pile-driving (e.g. Thomsen *et al* 2006, Nedwell *et al* 2007), however, indicate the high acoustic intensity of the impulses. Matuschek and Betke (2009) showed that emitted pressure and sound energy are correlated with pile diameter and can reach up to an $L_{\text{p–p}}$ of 200 dB re 1 μPa and 177 dB re 1 μPa^2 s broadband sound exposure level (SEL) at 750 m distance for piles $\geq$4 m diameter (units as defined in Ainslie (2011)).

Gilles *et al* (2009) presented a risk analysis based on the results of aerial surveys and the assumption that all 18 permitted wind farms (at that time) are constructed simultaneously in the German North Sea. They concluded that 39% of the harbour porpoises in the region could show behavioural reactions in this worst case scenario, as spatial overlap exists between important areas for porpoises and areas where offshore wind farms were licensed or planned. These scenarios can only be put into perspective when other threats to porpoises, like by-catch (e.g. Kock and Benke 1996, Vinther and Larsen 2004), pollution (Jepson *et al* 2005) and other anthropogenic noise (e.g. Wright *et al* 2007, Sundermeyer *et al* 2012) are evaluated as well.

In this study the seasonal and spatial distribution of harbour porpoises were analysed by means of aerial surveys while the habitat use and behaviour were investigated with passive acoustic monitoring methods using porpoise detectors (C-PODs; Chelonia Ltd, UK) aiming to characterize the effects of pile-driving noise for a relatively small wind farm (12 turbines). Especially changes in the spatial distribution, presence patterns and the influence of seasonal variations on presence/absence of porpoises were analysed.

2. Material and methods

2.1. Study area and harbour porpoise occurrence

The study concentrated on the area of the AV test site for offshore wind turbines, located 45 km north of the island of Borkum, in the southern German North Sea (figure 1). The small wind farm ($\sim$4 km^2) was built in an area with 30 m water depth characterized by a homogenous sediment structure mainly consisting of fine sand (Reichert *et al* 2012).

During studies conducted in the German EEZ between 2002 and 2006 the density of harbour porpoises in the southern German North Sea increased from 2004 onwards, mainly in spring (Gilles *et al* 2009). These findings are in line with observations in The Netherlands, Belgium and northern France (Kiszka *et al* 2004, Camphuysen 2011, Haelters *et al* 2011, Scheidat *et al* 2012) as well as with results of the SCANS-II survey from July 2005 (SCANS-II 2008). SCANS-II found no evidence for a change in abundance between SCANS in 1994 and SCANS-II in 2005. However, spatial modelling suggested a large shift in distribution of harbour porpoises from the northern waters to the south (Hammond *et al* 2002, 2013, SCANS-II 2008). Between 2002 and 2006 a strong seasonal variation of porpoise density was observed in the southern German North Sea (area D in Gilles *et al* 2009), with the highest density estimated for spring (March–May, 0.85 individuals km^{-2} (ind. km^{-2}), 95% CI: 0.45–1.72 ind. km^{-2}) and the

[6] www.bmu.de/english/transformation_of_the_energy_system/general_information/doc/48050.php, accessed: 10.01.2013.

[7] www.bmu.de/english/transformation_of_the_energy_system/resolutions_and_measures/doc/48054.php, accessed: 10.01.2013.

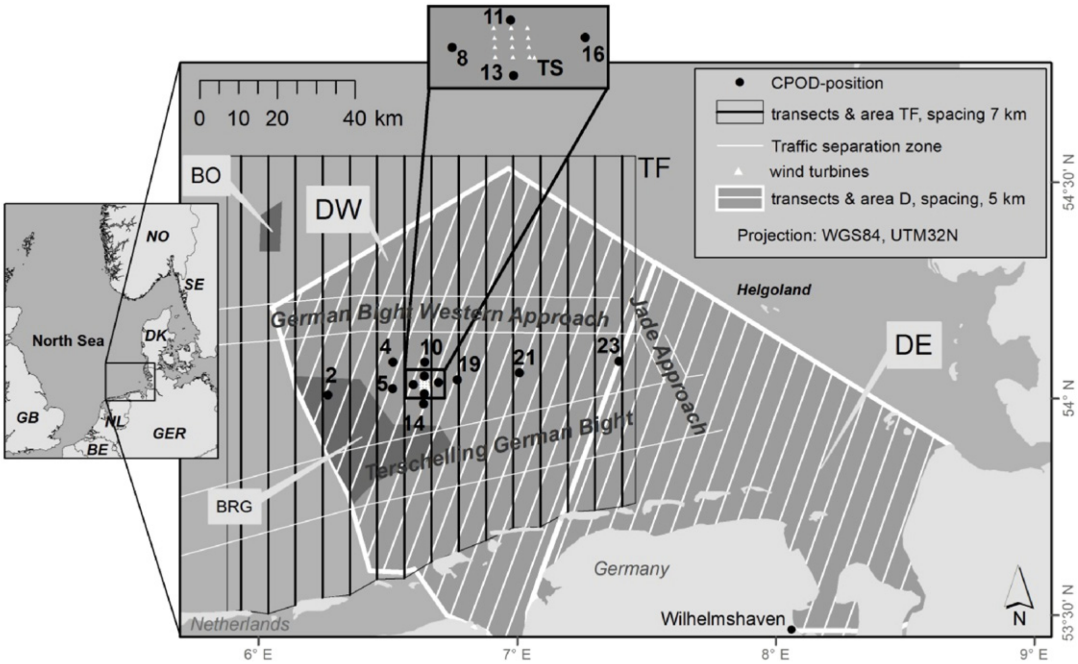


Figure 1. Study areas monitored between August 2008 and October 2010 (aerial surveys) and August 2008 and November 2011 (C-PODs; black dots). Small inset shows the location of the foundations (white triangles) and C-POD-locations closest to the wind farm (TS—transformer station, TF—aerial survey area TF, DW—western stratum of aerial survey area D, DE—eastern stratum of aerial survey area D, BRG—SCI Borkum Reef Ground, BO—BARD Offshore 1). Countries: GB—United Kingdom, NO—Norway, SE—Sweden, DK—Denmark, GER—Germany, NL—The Netherlands, BE—Belgium.

lowest density for summer (June–August, 0.17 ind. km^{-2}, 95% CI: 0.08–0.36 ind. km^{-2}). During spring of several years a hot-spot, i.e. a discrete area of particularly high harbour porpoise density, was observed at the Borkum Reef Ground (BRG) in the south-western part of the German EEZ, probably serving as one of the two key foraging areas in German waters (Gilles *et al* 2009). In The Netherlands porpoise density was shown to vary between seasons as well (Scheidat *et al* 2012): for the survey area neighbouring the southern German North Sea ('Frisian Front'), densities were estimated to be 1.02 ind. km^{-2} (November 2008, 95% CI: 0.34–2.10 ind. km^{-2}), 0.52 ind. km^{-2} (April 2009, 95% CI: 0.11–1.26 ind. km^{-2}) and 1.107 ind. km^{-2} (March 2010, 95% CI: 0.484–2.488 ind. km^{-2}).

2.2. Pile-driving operations

In 2008, the transformer platform was installed by driving four piles for a jacket foundation from 18th to 25th September with a total duration of approximately 880 min. Prior to impact piling, piles were vibrated up to nine metres into the substrate for eight to 20 min and then piled with a hydraulic hammer (type Menck MHU500T) of up to 500 kJ energy (Betke and Matuschek 2011). The same procedure was used for the first six wind turbines (type Areva Wind M5000, tripod construction; three piles per foundation) from 24th April to 1st June 2009. Pile-driving operation for the Areva Wind turbines lasted for 376–802 min per foundation using 14 665–25 208 hammer strokes. The remaining piles for the other six turbine foundations (type REpower 5M, jacket construction, four piles per foundation) were driven from 15th June to 26th August 2009 with durations of 530–561 min using 11 383–19 359 hammer strokes. Piling durations are depicted in figure 2. All pile diameters ranged between 2.4 and 2.6 m and piles were driven to approximately 30 m penetration depth (Betke and Matuschek 2011).

It has to be noted that the pile-driving of each of the first six foundations for the Areva Wind turbines (AV07-12) was conducted in less than 36 h on average while the remaining six foundations for REpower turbines (AV01-06) took up to several weeks each. The intervals between pile-driving activities, some lasting only for a few minutes, extended to a maximum of more than five days.

Two types of acoustic harassment devices (pingers and seal scarers) were used prior to piling to displace harbour porpoises and seals from the potentially harmful zone in which a temporary threshold shift (TTS) for harbour porpoises could occur (Lucke *et al* 2009). A code of conduct defined that first pingers and seal scarers were switched on simultaneously 30 min before pile-driving, however, this was not met in a systematic way during the installations. In addition, devices were switched off (1) after pile-driving for the designated foundations of the Areva Wind turbines and (2) with the beginning of the pile-driving operation of the REpower foundations. Therefore, the effect of pile-driving has to be considered as a combined effect of pile-driving and harassment, especially for stations at close range, but not for great distances (discussed in Brandt *et al* 2011).

Noise levels of pile-driving impulses were reported to vary in SEL from 154 to 175 dB re 1 μPa^2 s at 750 m

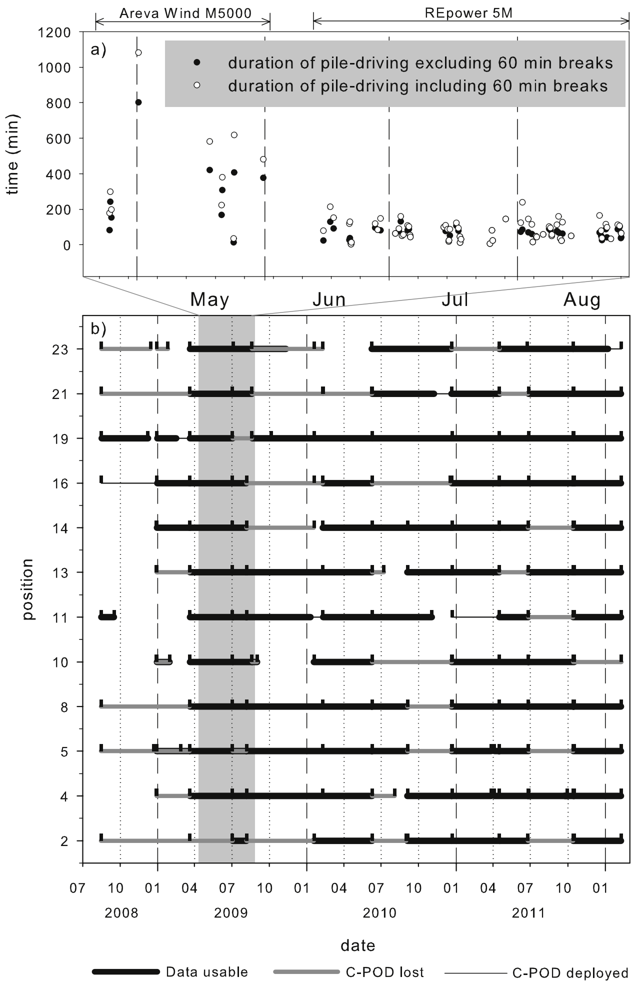


Figure 2. (a) Pile-driving times at single days in 2009, including periods with no pile-driving of up to 60 min (circles) as a measure for how long the whole process took with shorter breaks when a return of porpoises to the area is improbable and pile-driving durations only (black dots) in 2009 and (b) deployment periods of C-PODs 2008–11, ticks indicate servicing intervals.

distance (Betke and Matuschek 2011). Median SEL values of 157 dB re 1 μPa^2 s at 750 m distance were calculated from observations in greater distances during the test of an air bubble curtain at one of the foundations (for noise mitigation, 31st May to 1st June 2009, strongest attenuation of 10–12 dB downstream). With no such noise mitigation calculated median SEL ranged from 164 to 170 dB re 1 μPa^2 s in 750 m distance (Betke and Matuschek 2011). There was no apparent difference in SEL for the two foundation types. Using the empirical prognosis formula for transmission loss (TL) of Betke and Schultz-von-Glahn (2008):

$$TL = (10 + 2 \cdot \log(\mathit{frequency}) + (2.5 \times 10^{-8} \cdot \mathit{frequency} + 2 \times 10^{-5}) \cdot \mathit{radius}) \cdot \log(\mathit{radius}) \quad (1)$$

a SEL of 164–170 dB re 1μPa^2 s in 750 m distance would result in SELs of 146–152 dB in 10 km; 139–145 dB in 25 km and 131–137 dB in 50 km for a typical pile-driving centre frequency of 250 Hz. Betke and Matuschek (2011) however note that this formula most probably overestimates sound levels in distances larger than 10 km.

2.3. Aerial surveys

Dedicated aerial surveys following standard line transect distance sampling techniques (Buckland *et al* 2001) to assess density and distribution of harbour porpoises were conducted between August 2008 and October 2010. The area of the AV wind farm was covered by two survey areas (figure 1): area TF (10 934 km^2) was designed for studying the large scale effect of wind mill construction on porpoise presence as well as spatio-temporal trends. Therefore, the study area design comprised a 60 km radius around AV. The area D (11 824 km^2) was stratified in two strata (DE and DW), which could each be surveyed in one day (Gilles and Siebert 2009). Surveys in D are part of the national monitoring programme in the area of the BRG, a shallow sand bank with reef areas in 18–33 m depth of which the western part has been designated as a NATURA 2000 site (status SCI) (Krause *et al* 2006). In order to provide equal coverage within each survey area we selected a parallel transect layout in DISTANCE 5.0 (Thomas *et al* 2010) with tracks spaced seven km (area TF) and five km (area D) apart. In area TF, we placed transects in a north–south direction, parallel with water depth gradients, as transect direction should be perpendicular to the contour lines of physical or biological features (Buckland *et al* 2001). Transects in area D were placed at 60° to the shore to adapt the survey design to a north–south as well as west–east porpoise density gradient that has been described for this near shore area (Gilles *et al* 2009).

Aerial surveys were flown at 90–100 knots (167–185 km h^{-1}) at an altitude of 600 ft (183 m) in a Partenavia P68, a twin-engine, high-wing aircraft equipped with two bubble windows to allow scanning directly underneath the plane. The survey team consisted of two observers, one data recorder (navigator) and the pilot. Surveys were only conducted in sea conditions Beaufort 0 to <3 and with visibilities >5 km. Environmental conditions were recorded at the beginning of each transect and updated with any change. Conditions included (1) sea state, (2) water turbidity (3) percentage of cloud cover, and for each observer side, (4) glare (angle obscured by glare and intensity of glare) and (5) the observer's subjective view of the likelihood that, given all of the conditions, they would see a harbour porpoise should one be present. These subjective conditions could be good, moderate or poor. Detailed field and analyses protocols are described in Gilles *et al* (2009). Estimation of effective strip widths and $g(0)$, following the racetrack data collection method (Hiby and Lovell 1998, Hiby 1999), allowed for precise effort correction and accounted for missed animals and sighting conditions (Scheidat *et al* 2008), taking into account both the availability and the perception bias (Marsh and Sinclair 1989, Laake *et al* 1997). All data recorded in poor sighting conditions were excluded from subsequent analysis. The total effective strip width was estimated to be 153 m (SD = 0.0452) under good conditions and 54 m (SD = 0.0162) under moderate conditions, incorporating $g(0)$

values of 0.37 and 0.14, respectively. Animal abundance was estimated using a Horvitz–Thompson-like estimator (see Scheidat *et al* (2008) for details). Coefficients of variation (CV) and 95% confidence intervals (CI) were estimated by a non-parametric bootstrap test (999 replicates) within strata, using transects as the sampling units. The subjective assessment of good and moderate conditions, assessed separately for the left and right side of the transect, was used to define sections completed under consistent conditions. For the spatial analysis in ArcGIS 9.3 a grid with a resolution of 5×5 km was created. The overall number of harbour porpoises (n_i) and the effectively searched area (EA_i) per grid cell i were determined, and mean density estimates were calculated by the ratio n_i/EA_i (see Gilles *et al* (2009) for more details).

2.4. Static acoustic monitoring

The C-POD is a fixed autonomous logging device designed to passively detect odontocete echolocation clicks in the frequency range between 20 and 170 kHz (www.chelonia.co.uk). It uses digital waveform characterization in an online data processing to register click events and their time of occurrence, frequency, intensity, envelope and bandwidth. Most of those parameters are derived from automated analysis of zero-crossings to save battery power and processing time compared to a full spectral wave form or frequency analysis. This information is used as input to an off-line automated train detection and classification algorithm (version 1 was used within the study). C-POD detection range may vary depending on the existing background noise level and instrument variation, within a maximum of several hundred metres. For T-PODs, the predecessor of the C-POD, it has been established that the effective detection radius for harbour porpoises can range up to the low hundred metres (Kyhn *et al* 2008, 2012). Data were automatically processed with the proprietary software C-POD.exe version 1.017 using the settings for 'porpoise-like' click sequences in the classes 'Hi' and 'Mod'. The output format was chosen as 'detection positive 10 min' (*dp10min*, i.e. 10 min periods with at least one porpoise click train detection) as a relative measure for porpoise presence per day and hour (*dp10min/d* or *dp10min/h* respectively) and 'waiting times' (WT; interval length of periods of more than 10 min without detections given in minutes) as a measure for absence. First WT were defined as the WT ending with the first porpoise detection after pile-driving was commenced. Second WT was defined as the WT following first WT. First WT is used as a measure how long porpoises are displaced during and after the piling events.

12 positions equipped with C-PODs were regularly serviced every three months, from August 2008 to November 2011. C-PODs were located in an area of 80 km × 30 km stretching in the west from the Dutch border between two traffic separation zones towards the Jade Approach in the east (figure 1). Individual C-PODs were rotated between positions to distribute any error caused by instrument variation between positions. The northern and southern boundaries were set by two shipping lanes for large commercial vessels. This design of C-POD-locations allowed to determine potential gradients in harbour porpoise presence and habitat use along an east–west transect (i.e. parallel to the coastline and depth contours) as well as from the north to the south (i.e. with decreasing water depth). All positions on the east–west transect were placed at comparable distances to the shipping lanes to eliminate bias due to shipping activity. The C-PODs (V0 and 1) were calibrated in a tank prior to deployment, between data acquisition when problems with an individual C-POD occurred, after loss/retrieval and after the study ended. The methodology is further described in Dähne *et al* (2013) and Verfuß *et al* (2010). C-PODs were deployed 10 m above the seafloor in water depths between 25.5 and 34.5 m, i.e. approximately in mid-water to eliminate potential bias by wave and sediment noise.

When referring to pile-driving within this paper in statistical analyses and results, it has to be noted that in close range of the pile-driving site the displacement of porpoises is a combined effect of acoustic harassment devices and pile-driving. Statistical analysis did not allow for a separation of these effects. Hence, we only considered pile-driving as the presumably further reaching effect (Brandt *et al* 2011) and times are only given for the conduction of pile-driving.

2.4.1. Effects of pile-driving on dp10min/h. Generalized additive models (GAM, Hastie and Tibshirani 1990, Wood 2006) were developed for every station independently to determine the pile-driving effect on the presence of porpoises with a focus on the comparison of hours with and without pile-driving activity at the wind farm site of the years 2008–10. Response variable was the assumed Poisson distributed *dp10min/h*, corrected for overdispersion using a quasi-GAM model and independent variables were year as a factor (F), *month* and *hour* of the day as smoothing splines (f) as well as *pile-driving* as a binary factorial variable (B), to test which factors influenced the detection rates:

$$E[dp10min/h_i] = F_{(year_i)} + B(piledriving_i) + f(hour_i) + f(month_i). \quad (2)$$

2.4.2. Duration of the effects. The second analysis was carried out to find out how long the effect of pile-driving lasted. Waiting times as a measure for absence of porpoises from the pile-driving area were tested whether they were significantly influenced by *pile-driving* using a generalized linear mixed model (GLMM, McCullagh and Nelder 1989). The first *WT* after pile-driving was used as the dependent, while *month* and POD *position* were included as random factors (*re*) to account for variation caused by seasonality and geographic position. The *duration* of pile-driving (as factor, F) was included to investigate whether duration of pile-driving affected the first WT:

$$E[firstWT_i] = F(duration_i) + re(position_i) + re(month_i). \quad (3)$$

Significance of duration was tested using a log-ratio test as well as residual and q–q plots for a quality check of the model fit (Bates *et al* 2011).

In a following step WT of 2010 and 2011 were used as baseline data, assuming that effects of the operating wind farm would be less severe than habitat exclusion during pile-driving. 2011 was the first year of full operation with less ship traffic than in 2010 (increased ship traffic in 2010 due to final work at turbines). The so-called 'bus-paradox' (Ito *et al* 2003, Tougaard *et al* 2009) has an influence on this analysis: long WT have a higher probability of being selected by any randomization of a single point in time (like the end of pile-driving), falling into a random period, than short WT, even if these are dominant in a frequency distribution. Hence, the mean or median of randomly selected first WT based on any point in time will have a high probability of being longer than those of second and following WTs. This is true for the first WT after pile-driving, but is also true for any randomly selected one. To take account of this paradox, we have randomly selected WT from 2010 and 2011 based on a bootstrapping procedure for each month 500 times separately to have an unbiased estimate for the first WT not affected by pile-driving. The impact of pile-driving was therefore tested by using a binomial variable *pile-driving* and modelling its impact on the first WT accounting for seasonal and geographic variation by including *month* and *position* as random factors. Months without pile-driving activity in 2009 were excluded to restrict the analysis on the season when pile-driving was conducted. All WT were tested with a GLMM assuming a Poisson distribution:

$$E[firstWT_i] = B_1(piledriving_i) + re_1(position_i) + re_2(month_i). \quad (4)$$

To take account of possible temporal correlation in the data we included an autocorrelation structure based on auto-regressive moving averages (ARMA) for residuals from the nlme package (Pinheiro *et al* 2011).

2.4.3. Displacement of harbour porpoise due to pile-driving. In a third analysis the calculated distance (*dist* in km) from the actual pile-driving position to the individual C-POD-position was tested for significant influences on porpoise detection rates using two generalized additive mixed models (GAMMs; Lin and Zhang 1999, Wood 2006) with *dp10min* as response, *dist* as a smoother with four degrees of freedom (df) and *month* as a random factor. One model was built using only data from 10 min bins with pile-driving and the second model analysed situations without pile-driving.

$$E[dp10min_i] = f_1(dist_i) + re_1(position_i) + re_2(month_i). \quad (5)$$

The model predictions were plotted to show the displacement effect. All analysis were carried out using R 2.14.1 (R Development Core Team 2011) and the libraries lme4 0.999375-42 (Bates *et al* 2011), nlme 3.1-102 (Pinheiro *et al* 2011) and mgcv 1.7-13 (Wood 2011).

3. Results

3.1. Aerial surveys

Between 2008 and 2010, 15 dedicated aerial surveys for harbour porpoises were conducted in the area of the AV wind farm, of these three in area D (table 1). A total of 18 600 km of transect lines were surveyed and 1392 sightings of harbour porpoise groups were made on-effort. The number of sighted individuals totalled up to 1665, including 64 calves (table 1). For 10 of the 12 surveys conducted in area TF porpoise density could be estimated (figure 4), the remaining two surveys did not cover the area appropriately. In comparison to estimates in 2008 and 2010 lowest porpoise densities were estimated in 2009. As prominent seasonal differences in porpoise distribution and density were observed in the German Bight (Gilles *et al* 2009) an annual comparison of density estimates should only be investigated between same or adjacent months in different years. Results show that porpoise density in August 2009 was significantly lower than estimates in August 2008 and July 2010 (figure 4). In April 2009, at a survey date before pile-driving at AV had started, density was estimated to be 1.15 ind. km^{-2} (95% CI: 0.51–2.43 ind. km^{-2}), in May 2009 estimated density was lower with 0.72 ind. km^{-2} (95% CI: 0.38–1.46 ind. km^{-2}) and in May 2010 density was comparable to April 2009. Between 2008 and 2010 area DW was only surveyed in April, May and July 2009 and these densities were similar as estimated for TF during these months (figure 4).

In 2008 and 2009 eight flight days were conducted during periods with pile-driving activities at AV or within 48 h following pile-driving (table 1). Of these, only the survey at 1st May 2009 in area DW effectively overlapped in time with pile-driving at AV (3 h 23 min overlap; table 1) while surveying on transects in and around AV. In comparison to a survey conducted approx. one month before pile-driving had started (figure 3(a)), where porpoises were evenly distributed in the survey area and around AV, the observed distribution of porpoises at 1st May 2009 followed a different pattern. Very high porpoise densities were observed in the western and northern part of the study area (figure 3(b)) and no porpoises were visually detected in the vicinity of the construction site at AV; the nearest sighting was recorded at 20 km distance to the west of the driven pile.

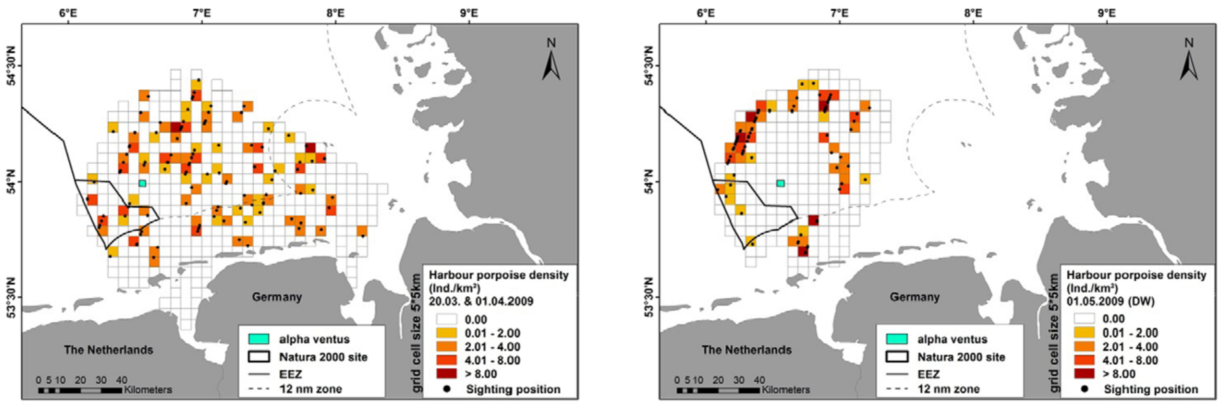
During all other surveys the area close to AV (i.e., in $<$15 km distance) was covered before or after pile-driving took place. Surveys which covered the area around AV shortly after pile-driving ceased were conducted in area D and TF in July 2009 (table 1). It has not been possible to estimate a robust density for the survey conducted in area TF on 14th July 2009 as the study area could not be covered in total, however, the encounter rate has been low (table 1). Area DW was surveyed on 3rd July 2009 about two hours following pile-driving: no porpoises were sighted in the area close to AV and the nearest sightings were recorded at distances of 13 km in the south. Density in D for July 2009 was estimated to be 0.58 ind. km^{-2} (95% CI: 0.27–1.25 ind. km^{-2}) which is comparable to the estimate for area TF in August 2009 and comparably lower than densities in 2008 and 2010 (figure 4).

Table 1. Harbour porpoise aerial surveys in the area of AV and exact timing of pile-driving as well as use of harassment devices (pinger and seal scarer). Effort = survey effort in good or moderate survey conditions. Time of pile-driving includes breaks of maximum 60 min.

Survey	Date	Area	Effort (km)	Sightings (no.)	Individuals (no.)	Calves (no.)	Encounter rate (sightings km^{-1})	Pile-driving (CEST)	Harassment (CEST)	Survey (CEST)	Time overlap with pile-driving
1	15.08.2008	TF	665	58	84	6	0.09	None	None		
	16.08.2008	TF	591	45	62	3	0.08	None	None		
	Sum		1 256	103	146	9	0.08				
2	18.09.2008	TF	951	58	67	3	0.06	Vibration on evening	None	9:56–13:13&14:54–17:34	
	19.09.2008	TF	748	32	41	3	0.04	13:20–14:10	11:50–14:30	10:09–12:46&15:05–17:11	None
	Sum		1 699	90	108	6	0.05				
3	20.03.2009	DE&DW	882	96	113	0	0.11	None	None		
	01.04.2009	DE&DW	721	18	23	0	0.02	None	None		
	Sum		1 603	114	136	0	0.07				
4	11.04.2009	TF	617	128	134	0	0.21	None	None		
	12.04.2009	TF	511	18	18	0	0.04	None	None		
	Sum		1 128	146	152	0	0.13				
5	23.04.2009	DE	849	19	19	0	0.02	None	None		
	01.05.2009	DW	995	77	89	1	0.08	01.05. 12:20–02.05. 6:22	01.05. 9:10–02.05. 4:45	9:53–12:20&14:16–17:39	3 h 23 min
	Sum		1 844	96	108	1	0.05				
6	23.05.2009	TF	844	72	75	1	0.09	21.05. 13:42–17:33 21.05. 18:38–22.05. 00:58	21.05. 11:55–22.05. 2:40	10:57–13:39&15:21–17:45	None
7	03.07.2009	DW	406	15	18	1	0.04	10:33–12:04, 20:39–23:18	4:40–5:40,18:10–19:10	13:57–16:31 (no break)	None
	05.07.2009	DW&DE	633	45	56	5	0.07	13:45–15:33, 20:54–22:36	12:45–16:00, 19:39–20:47	10:43–13:06&15:03–18:09	30 min
	Sum		1 039	60	74	6	0.06				
8	14.07.2009	TF	714	46	54	2	0.06	07:05–08:43&18:24-20:13	4:40–15.07. 00:00	10:40–12:41&14:29–17:08	None
9	10.08.2009	TF	860	28	31	1	0.03	15:15–17:07	13:35–20:20, 23:00–12.08. 0:00	09:34–11:54&13:20–15:47	32 min
	14.08.2009	TF	669	39	48	4	0.06	0:21–0:57, 2:20–2:59	13.08. 19:50–14.08 4:00	10:59–13:38&14:53–16:23	None
	Sum		1 529	67	79	5	0.04				

Table 1. (Continued.)

Survey	Date	Area	Effort (km)	Sightings (no.)	Individuals (no.)	Calves (no.)	Encounter rate (sightings km^{-1})	Pile-driving (CEST)	Harassment (CEST)	Survey (CEST)	Time overlap with pile-driving
10	18.09.2009	TF	575	3	3	0	0.01	None	None		
11	16.03.2010	TF	611	52	61	0	0.09	None	None		
12	11.05.2010	TF	810	59	66	0	0.07	None	None		
	14.05.2010	TF	724	119	133	1	0.16	None	None		
	Sum		1 534	178	199	1	0.12				
13	05.06.2010	TF	830	110	148	18	0.13	None	None		
	09.06.2010	TF	474	22	28	3	0.05	None	None		
	Sum		1 304	132	176	21	0.10				
14	10.07.2010	TF	777	114	145	7	0.15	None	None		
	23.07.2010	TF	716	45	50	2	0.06	None	None		
	Sum		1 493	159	195	9	0.11				
15	12.10.2010	TF	586	3	6	1	0.01	None	None		
	17.10.2010	TF	841	71	93	2	0.08	None	None		
	Sum		1 427	74	99	3	0.05				
	Σ	TF	14 114	1122	1347	57	0.08				
	Σ	D	4 486	270	318	7	0.06				
	Σ		18 600	1392	1665	64	0.07				



a) b)

Figure 3. Spatial distribution of harbour porpoise density and sightings. (a) Pre-pile-driving in March/April 2009 and (b) during pile-driving in DW (1st May 2009; DE was not surveyed during pile-driving at that particular time). Projection: WGS84, UTM Zone 32N.

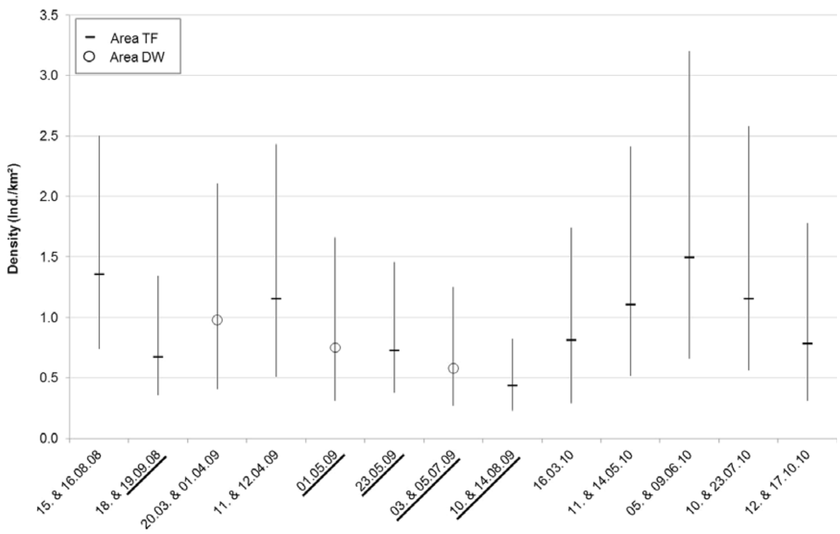


Figure 4. Estimated density of harbour porpoise per survey in the study areas TF and DW. Error bars show 95% confidence limits. Area TF is indicated by short dashes for the estimated density, area DW is represented by open circles. Dates of surveys conducted during pile-driving or within 48 h following pile-driving at AV are underlined in black.

3.2. Static acoustic monitoring

Devices had a mean 50% peak–peak detection threshold (received level where 50% of sent out clicks were detected by the device in a test tank) of 117.3 $\pm$ 2.6 (standard deviation) dB re 1 μPa at 130 kHz. For more details on the methodology please see Dähne *et al* (2013).

3.2.1. Effects of pile-driving on harbour porpoise presence (dp10min/h). *dp10min/h* showed a strong seasonal variation among all stations (e.g. station 11 and 19 in figure 5). Detection rates peaked from September to January and lows were encountered from late April to early August. Detection rates in the latter months in 2009 were close to zero. In 2010 and 2011 higher detection rates were encountered when compared to 2009. Construction work was unintentionally carried out during a period of low detection rates potentially caused by a combination of seasonal variation and pile-driving effects. The *dp10min/h* varied geographically, with less detections in closer vicinity of the wind farm and increased detection rates towards BRG.

Data analysis with GAMs depicted that not all stations showed the same temporal variation in *dp10min/h*. Eight stations within 10.8 km of the wind farm (except stations 10 and 2) showed a negative impact of hours when pile-driving was conducted in comparison to hours without pile-driving (table 2). Two stations showed significantly more detections during hours with pile-driving. These stations were deployed in a distance of about 25 and 50 km from the construction site (stations 21 and 23). The variable *month* had a significant impact in all models, while *year* was not significant at stations 2 and 23, and *hour* was not significant at station 19. Pronounced diurnal and seasonal variations were detected between stations (figure 6). Explained deviances varied from 3.84 to 20.07% showing that most of the variation cannot be explained by yearly, seasonal and diurnal variation in combination with pile-driving alone.

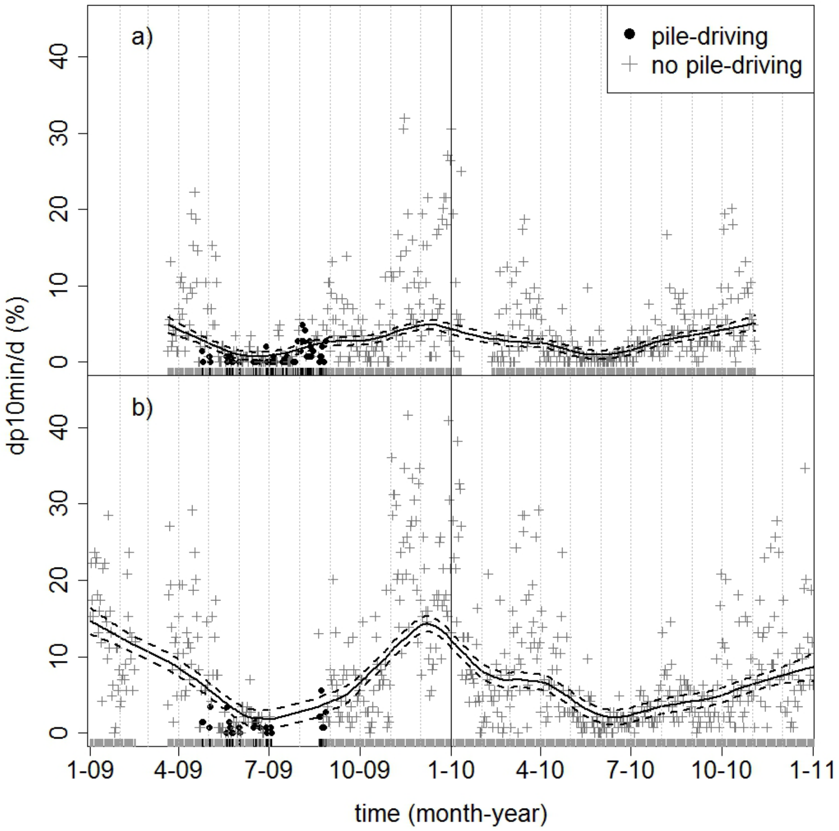


Figure 5. Detection positive 10 min periods per day (*dp10min/d*) for 2009 and 2010 at (a) station 11 and (b) station 19. Days with pile-driving are marked with black dots, days without pile-driving with grey crosses. The black line represents a smoothing spline with 95% confidence limits (dashed lines). Ticks below the plot represent available data points.

Table 2. Summary of the GAM-models, the intercept represents the modelled mean of the *dp10min/h* and the intercept of singular variables. n.s. = not significant, *n* = number of samples, Expl. dev. = explained deviance.

Position	Distance to piling site *min–max* (km)	*n*	Intercept	Intercept *pile-driving*	Effect	*p pile-driving*	*p year*	*p month*	*p hour*	Expl. dev. (%)
2	25.2–26	6848	0.99	n.s.	n.s.	n.s.	n.s.	<0.001	<0.001	8.23
4	8–10.8	13 315	0.88	−0.42	−	<0.001	<0.001	<0.001	0.025	10.87
5	7.4–9.8	12 039	−0.66	−1.24	−	<0.001	<0.001	<0.001	<0.001	17.08
8	2.3–4.6	12 838	0.42	−1.36	−	<0.001	<0.001	<0.001	<0.001	10.54
10	3.0–4.2	5602	1.08	−0.61	n.s.	n.s.	<0.001	<0.001	<0.001	19.84
11	0.5–2.5	14 226	0.00	−1.16	−	<0.001	<0.001	<0.001	<0.001	13.92
13	2.3–4.7	12 823	−0.55	−0.86	−	<0.001	<0.001	<0.001	<0.001	6.46
14	4.5–7.0	12 846	2.22	−0.81	−	<0.001	<0.001	<0.001	<0.001	8.90
16	2.5–4.5	11 286	0.76	−1.67	−	<0.001	<0.001	<0.001	0.003	20.07
19	7.2–9.2	14 970	1.28	−1.51	−	<0.001	<0.001	<0.001	0.095	16.81
21	23–25	7283	−1.81	0.25	+	0.005	<0.001	<0.001	<0.001	13.81
23	48.7–50.5	9406	−0.62	−0.54	+	<0.001	n.s.	<0.001	<0.001	3.84

The C-POD data showed an increase in harbour porpoise presence towards the end of the piling period in August/September 2009, i.e. during the installation of the last three foundations (figure 5).

3.2.2. Duration of the displacement effect. WT strongly varied throughout the seasons with elevated WT between April and August in all years (figure 7). The first *WT* between successive harbour porpoise detections during pile-driving, including mitigation in 2008 and 2009, showed median values ranging from 81 min (position 2) to 1444 min (position 11) with a median of 1008 min (for all positions) and a maximum of 8468 min (position 13) (figure 7). Only a single porpoise detection was registered during pile-driving operation on position 11 at 1.03 km distance from the piling site on 29th July 2009 from 7:52 to 8:12 CEST; pile-driving started that day at 06:06 and lasted until 08:30. Acoustic harassment devices were operating from 01:30 to 08:45 that day. All other detections at the four closest C-PODs were in distances greater than 1.7 km from pile-driving. There is a general

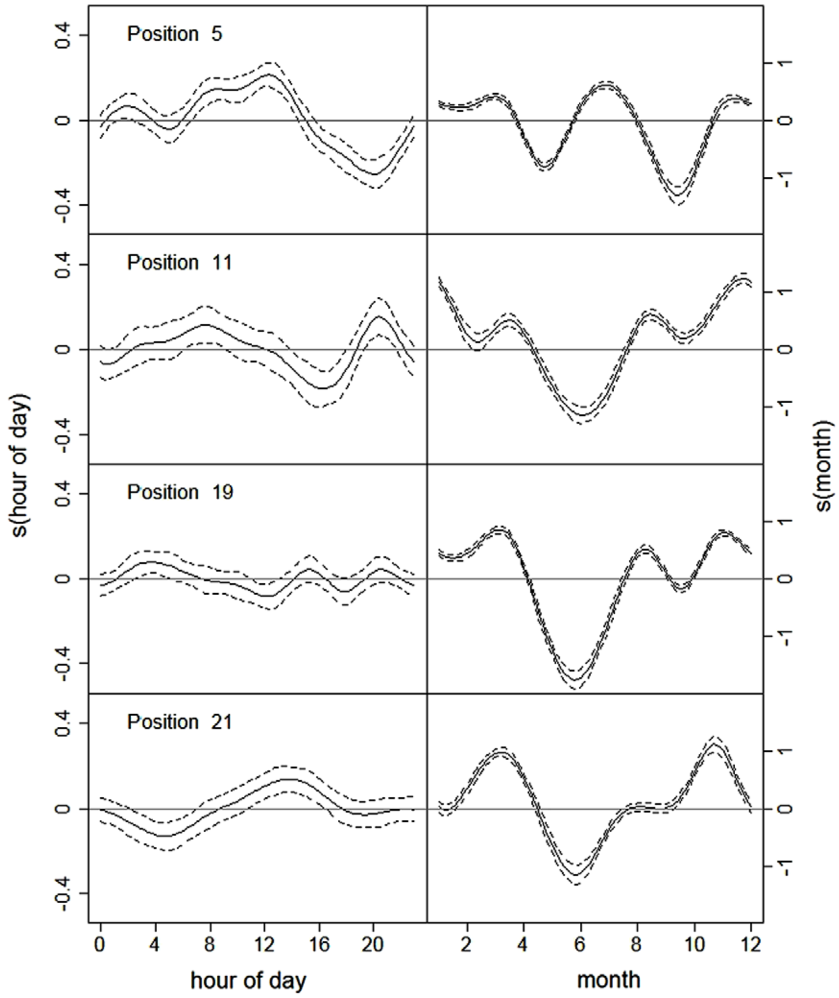


Figure 6. Smoothing splines (s) of generalized additive modelling at stations (a) 5, (b) 11, (c) 19, (d) 21 over the years 2008–2010. Significance of the results is displayed in table 2.

trend towards lower first WT close to the surrounding of the construction site (i.e. <3 km) after consecutive, but shorter pile-driving sequences during the installation period of all 12 turbine foundations in summer 2009 (figure 7).

Mean WT in the study area at different positions were generally comparable ranging from 46 to 60 min, except for stations close to BRG (2, 5 and 14) showing lower WT (median of 34, 35 and 38 min, respectively) and position 23 with slightly elevated median WT of 67 min (figure 7). These stations and station 23 showed the least effect by pile-driving activity on the first WT. Second WT were generally more randomly distributed in all WT (figure 7). The linear mixed effects models showed significant effects of *pile-driving* ($p < 2.2\times10^{-16}$, correlation of fixed effects: -0.048, $t = 12.8385$) and *duration* ($p < 2.2 \times 10^{-16}$, correlation of fixed effects: -0.008, $z = 33.61$) in their respective log-ratio tests. With increased duration of pile-driving the WT also increased, even though the effect of seasonality has been considered within the model. Hence, the effect of *pile-driving* can only be considered when *duration* of pile-driving is taken into account. First WT increased to a median of 16.5 h during pile-driving within 25 km of the source. This represents a modelled increase of first WT compared to WT chosen by a randomized date/time from 2010 and 2011 of 9.9 h.

3.2.3. Displacement of harbour porpoise due to pile-driving. The GAMMs constructed from only *dp10min* with or without pile-driving showed a clear effect of the two random factors *month* and *position*, as well as *dist*. Model predictions had a reduced probability of detection during pile-driving at all stations within a radius of 10.8 km as the two model predictions (with/without pile-driving) do not overlap (figure 8). There is a data gap between 10.8 and 23 km. A certain amount of overlap exists for positions with distances larger than 20 km from AV. It must be noted that the model for pile-driving predicted zero or nearly zero values even in distances up to 50 km from the source.

4. Discussion

Two large scale surveys in European waters (SCANS and SCANS-II) showed that harbour porpoise distribution can shift within a decade, possibly due to a change in prey occurrence in the North Sea (Hammond *et al* 2002, SCANS-II

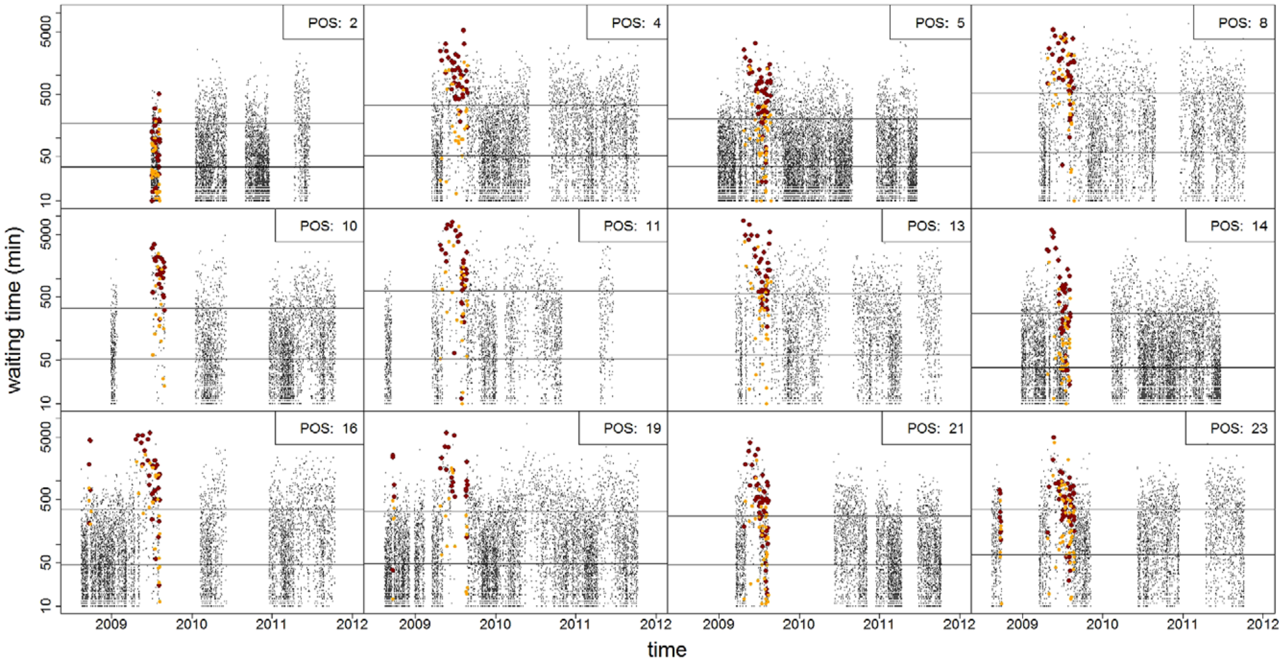


Figure 7. Analysis of waiting times (WT) for each C-POD-position. Grey dots mark WT without pile-driving and red dots mark 1st WT after pile-driving was commenced, orange dots are 2nd WT after pile-driving. The horizontal black line and grey line indicate respectively the median and the median + standard deviation of all WT at that position. *Y*-axis is log scaled.

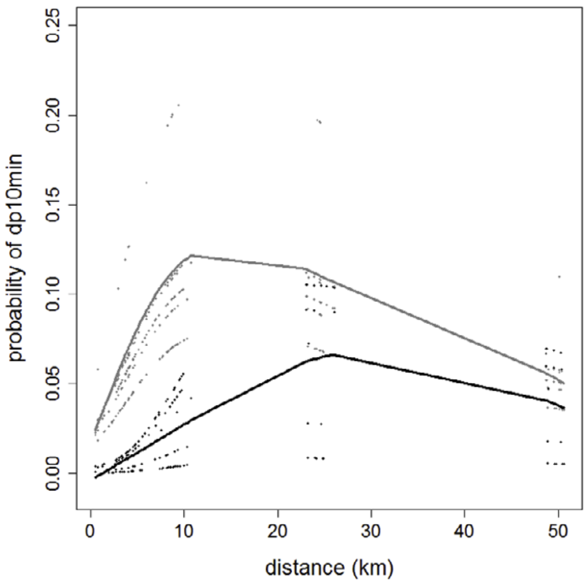


Figure 8. Behavioural changes at different distances to pile-driving analysed with two GAMMS. Grey: GAMM constructed from the *dp10min* without pile-driving; distance was calculated towards the centre of the wind farm. Black: *dp10min* for days when pile-driving was conducted; distance was calculated for each piling event individually. The *x*-axis displays the calculated distance to the pile-driving operation; the *y*-axis depicts predicted values of the probability to detect a positive *dp10min*. Lines represent a smoothing spline with 5 df for each model.

2008). Dedicated visual surveys are indispensable for robust abundance estimation within a predefined study area, but it is challenging to detect changes in distribution and density to a degree, that would be helpful for small scale wind farm impact studies. Hence, these survey methods have to be combined for instance with static acoustic monitoring, that proved to be effective within environmental impact studies on small scales (Carstensen *et al* 2006, Tougaard *et al* 2009, Brandt *et al* 2011).

4.1. Aerial surveys

The survey conducted during pile-driving on 1st May 2009 showed a possible strong avoidance reaction of harbour porpoise during construction. Three circumstances have to be considered: (a) acoustic harassment devices were switched on for a long time prior pile-driving; (b) pile-driving activities lasted for a prolonged time (1st May 2009: 9.5 h pure pile-driving time, 11.5 h including breaks for up to 60 min, when a return of porpoises to the area is at least uncertain); (c) logistics: the exact timing of the survey fitted to pile-driving activities. In order to conduct successful and representative visual surveys for harbour porpoises it is of uttermost importance to survey in good weather periods, with a calm sea surface and good visibility (Gilles *et al* 2009). Therefore, not all surveys could be timed to fit perfectly well to actual pile-driving activities or were conducted during shorter pile-driving sequences. Lower densities were estimated for 2009, compared to 2008 and 2010. This change in porpoise abundance cannot be solely attributed to the pile-driving activities at AV as other factors influencing porpoise presence, like e.g. prey availability or other anthropogenic activities need to be considered as well within this survey area. However, the event on 1st May 2009 shows that avoidance can be documented by aerial surveys, representing a snapshot method, under certain conditions. The pronounced difference in the distribution between the surveys before (March/early April 2009) and during construction (May 2009) is clearly indicating that the first construction activities at the AV test field had an influence on porpoise distribution. The most sensible explanation for the documented effects is a reaction to the sound emissions as no other sensory input would last over such vast distances. Moreover, harbour porpoises have been shown to have a very sensitive hearing and react to underwater sound (Andersen 1970, Kastelein *et al* 2002, 2010). Lucke *et al* (2009) showed that aversive behavioural reactions of a captive harbour porpoise were initiated at a received SEL of >145 dB re 1 μPa^2 s which corresponds to a distance of >10 km (146–152 dB re 1 μPa^2 s calculated SEL) and <25 km (139–145 dB re 1 μPa^2 s calculated SEL) around the AV pile-driving site coinciding approximately with the observed avoidance distance of porpoises detected during the aerial survey on 1st May 2009, when only three porpoises were sighted within 25 km from the pile-driving operation. Calculated SELs are probably overestimates (Betke and Matuschek 2011). Hence, a displacement may be caused by smaller SELs than reported here. Therefore, future studies should include the use of automated noise loggers to have a better basis for evaluation of the effects, especially in distances larger than 10 km.

The effect of deterrence devices and pile-driving must be considered as a combined effect for stations close to the source, as deterrence devices were switched on and off during and before pile-driving without a clear pattern, which should be implemented into sophisticated modelling approaches.

4.2. Static acoustic monitoring

The avoidance effect documented by the aerial survey on 1st May 2009 is confirmed in its spatial extent by the C-POD data which showed a significant negative correlation between pile-driving activity and the presence of harbour porpoises over a range of at least 10 km from the wind farm site. This effect is gradually decreasing towards 50 km as the farthest distance where C-PODs were deployed. WT increased up to a maximum of 8468 min (~6 days, station 13, distance 1.7 km) showing that the pile-driving impact can last for a long time during periods of generally low porpoise detection rates. Additive mixed modelling allowed to confirm that seasonality, diurnal rhythm, as well as pile-driving influence porpoise distribution and habitat use. The higher detection rates at 25 and 50 km distance showed that porpoises were possibly displaced towards these stations. This implies that a behavioural reaction cannot be defined by a potential displacement radius alone, but could reach further as an increase in detection rates can also be seen as a behavioural reaction. It is not clear to us whether the longer piling events led to a complete spatial displacement in terms of a stationary situation, where in- and outflow of porpoise into the affected area are balanced, as first WT and duration of pile-driving were correlated. Hence, it could be that porpoises were not completely displaced to a range where they would naturally stop to further move away. If that is true then porpoises were probably exposed to multiple sound events above their behavioural reaction threshold over long time periods up to distances of 50 km. Sound propagation effects lead to a high uncertainty of predicted SELs by formula (1) in great distances. As a consequence, future research should also focus on developing applicable prediction models and measuring the noise level directly at the C-POD.

The increase in harbour porpoise detection rates in late summer 2009 cannot be unequivocally explained—it could either be due to seasonal variation caused by a high abundance of preferred prey, disturbance or deteriorating conditions in adjacent areas, habituation or other factors (each in combination). However, the detection of a harbour porpoise click train close to on-going pile-driving gives reasons for severe concern about the acoustic exposure of these animals to the piling impulses. It took on average more than 15 000 piling strikes to install each turbine (a tripod or jacket construction installed on three to four pile foundations) with SELs calculated of up to 175 dB re 1 μPa^2 s in 750 m distance (Betke and Matuschek 2011). Each individual that returned to the construction site and remained during the pile-driving period was consequently exposed to a high number of strikes at considerable noise levels, thereby accumulating the acoustic energy in its hearing system. A limit for temporary threshold shift of received $L_{\text{p–p}}$ of 200 dB re 1 μPa/SEL of 164 dB re 1 μPa^2 s was determined for a harbour porpoise in captivity for an exposure to single impulses (Lucke *et al* 2009). Consequently, it is one hypothesis that in the case of regular pile-driving without noise mitigation measures a number of animals suffered a temporary auditory impairment. The results of the study cannot validate whether the same individuals were exposed multiple times, or if the ecological and/or prey preferences led to an inflow of acoustically unaffected animals. Results from the North Sea (Tougaard *et al* 2009, Brandt *et al* 2011) showed that the effect of the construction of a wind farm was short-term, while results from the Baltic Sea (Carstensen *et al* 2006) suggested a possible longer lasting reaction. When considering the health status of these animals being already under pressure by pollution, habitat deterioration due to (over-)fishing, non-target by-catch and other noise sources, it is very probable, that at least some animals cannot react sufficiently fast. For instance swimming speeds are naturally reduced for mother-calf pairs. This could explain why one detection occurred at one kilometre from the wind farm during pile-driving. Multiple displacements could lead to elevated stress levels in addition to a possible hearing impairment.

Along with the possible impact of pile-driving on the auditory system and physiological consequences, a temporal displacement from a potentially optimal habitat needs to be considered. Multiple simultaneous construction activities are for instance planned within close vicinity of the Natura 2000 site 'Sylt Outer Reef' where a large proportion of the local harbour porpoise population reproduces (Gilles *et al* 2009, 2011). This could potentially lead to a reduction in fitness of individual animals, and due to possible disturbance during feeding and mating, to a reduction of fitness of the population in places of high abundance where prey availability, but also the competition for food, is higher.

The main challenge of future research will be to determine whether the construction, operation and decommissioning of offshore wind farms has population level effects for harbour porpoises or not (NRC 2005). To achieve such insight, it will be necessary to use all available methodologies within a coordinated framework as presented here. Right now all studies on effects of wind farms on porpoises are mainly based on measurements with stationary moored acoustic data loggers. While this methodology allows for a very detailed analysis of short-term reactions (Carstensen *et al* 2006, Tougaard *et al* 2009, Brandt *et al* 2011) as well as long-term changes in habitat use (Scheidat *et al* 2011) it is not yet clear how to link those results to the status of the population and what would be the influence of a simultaneous construction of a number of wind farms on porpoise distribution, habitat use, health and reproductive success. It may be necessary for future studies to involve additional large scale aerial surveys over long periods before, during and after pile-driving to establish such a link.

5. Conclusion

Using large scale aerial surveys and extensive SAM it was possible to analyse the effects of pile-driving in more detail than previously reported. Pile-driving SELs between 139–145 (25 km) and 146–152 (10 km) dB re 1 μPa^2 s most probably lead to a displacement of harbour porpoises, which could be seen in one aerial survey perfectly timed to pile-driving as well as on the C-POD data. These SELs are most probably overestimates indicating that the behavioural reaction threshold of harbour porpoises towards pile-driving sounds is lower. Within 25 km radius the median WT changed to 16.85 h during pile-driving. A major outcome is that the duration of pile-driving had a large impact on the WT with longer pile-driving durations leading to a longer displacement. Future research should be aimed at defining the consequences on the population level. This concerns on one hand multiple exposures in close vicinity of pile-driving during shorter pile-driving times and breaks including a potentially decreased fitness due to multiple flight reactions and energy expenditure. On the other hand a prolonged absence from the pile-driving site can result in a considerable temporal habitat loss. It is unclear which of those possibilities is potentially more threatening. The effect of noise mitigation measures like air bubble curtains and 'Hydro Sound Dampers' tested for instance by Würsig *et al* (2000), Lucke *et al* (2011) and Wilke *et al* (2012) will most probably have a reduction effect on displacements if used continuously during pile-driving.

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