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# Seal scarers as a tool to deter harbour porpoises from offshore construction sites

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ABSTRACT: Offshore pile driving, e.g. during wind farm construction, produces substantial noise emissions into the water column, which may harm marine mammals. Therefore, it is common practice to attempt to deter the mammals out of potential danger zones beforehand. Seal scarers are commonly used as a deterrent for harbour porpoises in spite of a lack of clear evidence in support of their effectiveness. We investigated the responses of harbour porpoises to a Lofitech seal scarer by conducting visual observations in conjunction with sound measurements. Porpoise sighting rates within 1 km of the seal scarer significantly decreased to only 1% during seal scarer activity. During 22 trials, when the seal scarer was deployed between 300 m and 3.3 km distance, all observed porpoises always avoided the seal scarer within 1.9 km (translating to sound levels of ≥122 dB re 1 µ$\text{Pa}_{\text{rms}}$), avoided the seal scarer half the time within 2.1 to 2.4 km (119 to 121 dB re 1 µ$\text{Pa}_{\text{rms}}$) and never avoided the seal scarer at distances beyond 2.6 km (≤118 dB re 1 µ$\text{Pa}_{\text{rms}}$). The closest observed approach distance of a porpoise to the activated seal scarer was 798 m (132 dB re 1 µ$\text{Pa}_{\text{rms}}$). Thus, the deployment of a Lofitech seal scarer during offshore pile driving activities can greatly reduce the risk of acoustic traumata to harbour porpoises. However, danger zones and thus the necessary deterrence zones have to be calculated specifically for each project based on measurements of sound transmission in the area.

KEY WORDS: *Phocoena phocoena* · Deterrence · Offshore windfarm · Behaviour · Pile driving · Marine mammal

## INTRODUCTION

As part of the worldwide expansion of renewable energies, offshore wind farming is planned on a large scale in many European countries. Most offshore wind farms are going to be installed on steel foundations that are driven into the seabed. This installation process produces considerable noise emissions into the water column, which leads to large-scale disturbance (Brandt et al. 2011) and may even reach levels that inflict physical damage to the sensory system of marine mammals (Madsen et al. 2006, Southall et al. 2007). While disturbance can only be mitigated by reducing noise levels during such operations, physical damage may be avoided by deterring marine mammals away from the vicinity of piling activities. In the North Sea, the harbour porpoise *Phocoena phocoena* is the most abundant marine mammal and is found in all coastal and offshore waters (Reid et al. 2003). The species is listed in Annex II and IV of the EU Habitats Directive, and deliberate killing or significant disturbance of this species are prohibited. Consequently, a permit to erect offshore wind farms often includes the condition to deter porpoises to a distance beyond which they may not suffer potential injury. Commercially

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available devices for deterrence include acoustic deterrents, also called pingers, and acoustic harassments, also called seal scarers. Pingers are designed to deter harbour porpoises from fish nets to reduce bycatch mortality and work effectively between 100 and 400 m (Cox et al. 2001, Culik et al. 2001, Carlström et al. 2009). Seal scarers were developed to keep seals away from fish farms and reduce economic damage due to predation. Seal scarers emit acoustic signals with a considerably higher source level and at a lower frequency range than pingers. Their deterrence effect on harbour porpoises may reach much larger distances (Johnston 2002, Olesiuk et al. 2002). When seal scarers are used to deter seals from fish farms, the much further-reaching deterrence effect on harbour porpoises is an unwanted side effect. Concern has been raised over the unwanted exclusion of porpoises from possibly critical habitat (Johnston 2002, Olesiuk et al. 2002, Götz & Janik 2010), as has been demonstrated for killer whales *Orcinus orca* in British Columbia (Morton & Symonds 2002). However, the potentially large deterrence effect on harbour porpoises may offer the opportunity to deter both seals and porpoises from danger zones produced during the pile driving activity required in offshore wind farm construction. Understanding the deterrence effect of a seal scarer is important if it is to be used to reduce the risk of marine mammal injury caused by offshore construction work.

## MATERIALS AND METHODS

### Study area and experimental setup

The study took place at Fyns Hoved, located on the northern side of the island Fyn in the Inner Danish Waters (Fig. 1). A central marker buoy was deployed 150 m off the coast, and 3 buoys each to the south, west and north were moored 150, 450 and 1000 m from the central buoy as visual markers (Fig. 1) to help with the localisation of the porpoises and to estimate distances. Observations were conducted from a 21 m high cliff that provided a good overview of the observation area with excellent tracking possibilities of harbour porpoises swimming near the coast up to a distance of ~1 km. The seabed sediment consists of mud and finer sand with intermittent large stones and boulders. The seafloor slopes gradually with water depth ranging between 2 and 15 m.

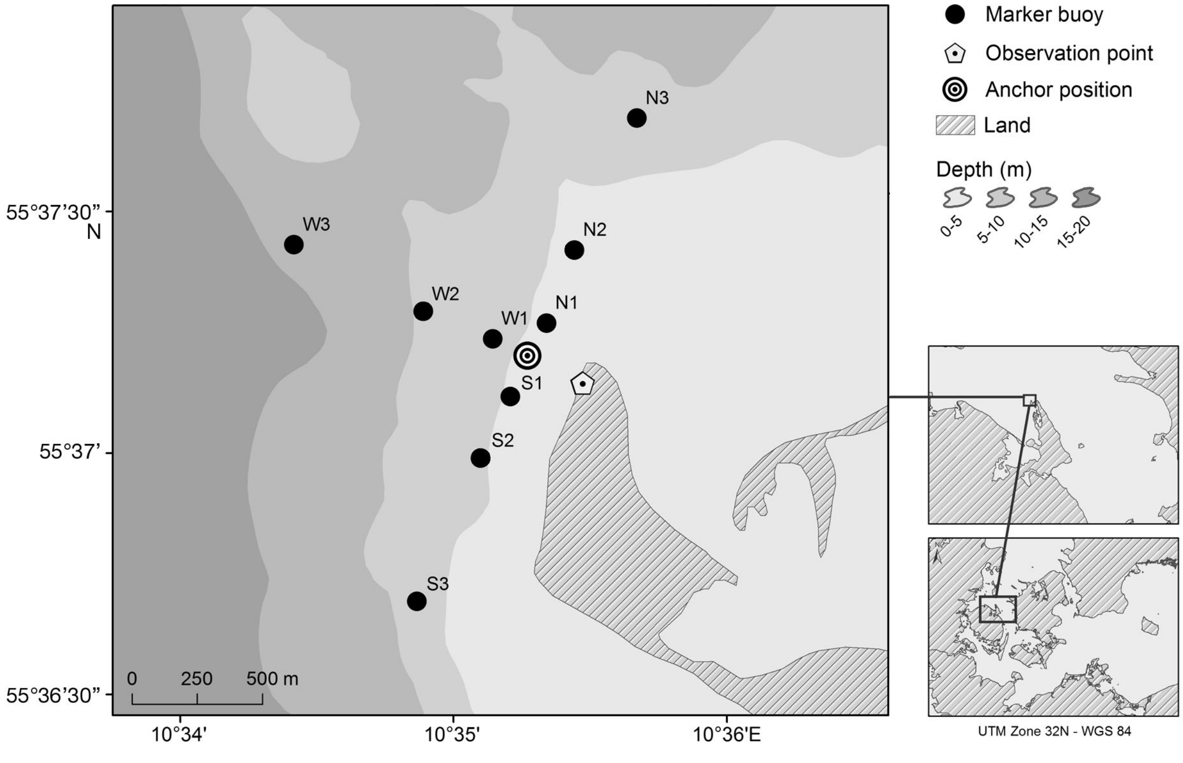

Fig. 1. Study area at Fyns Hoved showing anchoring position, marker buoys and observation point

### Experimental procedure

The experimental design followed 2 studies that have tested the effects of pingers (Carlström et al. 2009) and of an Airmar seal scarer (Johnston 2002) on harbour porpoises. From the observation point on top of the cliff, a radius of up to 1 km around the central anchoring position was observed for porpoise presence. Observers tracked animals using a theodolite (Geodimeter 468), which enabled determination of the animals' position when surfacing by using the known height of the observation point and the horizontal angle of the animals' position (e.g. Koschinski et al. 2003, Kyhn et al. 2012). Three persons (observer, tracker and recorder) were positioned at the land based observation point (Fig. 1) and switched tasks approximately every hour. Using a pool of only 6 different observers with similar experience and rotating their tasks frequently minimised potential observer-related differences in porpoise sightings.

Every 10 min the observer scanned the 1 km radius by the naked eye for the 150 m radius and by binoculars for the outer area up to 1 km radius around the central position. One complete scan took ~2 to 3 min. In between scans the area was constantly searched with the naked eye. For each sighting, the observer determined group size, group composition (adults or calves), behaviour, swimming direction, distance from the anchoring position, time and whether the observation occurred within or between standardised scans. Sighting conditions (sun glare) and sea state were monitored and recorded whenever they changed. Sea state was estimated following the Petersen state-of-the-sea scale (Petersen 1927).

The tracker used the theodolite to track the nearest sighted individual or group of harbour porpoises until they were out of sight. The recorder inserted the tracker's information into the computer connected to the theodolite (using Cyclops 3.1 real-time animal tracking software, www.cyclops-tracker.com). Usually porpoises could only accurately be tracked up to a distance of ~800 m before the location error became too large. Covering larger distances was only possible during a sea state of 0 to 1, when the footprint of the porpoises could be still seen.

A small boat with 1 person was always at the central anchoring position from the third day of observation onwards to operate the seal scarer regardless of whether real or sham exposures were conducted (Fig. 1). Observations started 15 min after the boat was anchored and the engine was switched off. Observations were conducted between 1 May and 7 August 2010 on days with a maximum sea state of 2. Nine days without, and 7 d with a seal scarer operation were completed. During the first 4 d we deliberately collected baseline data, where porpoises were not influenced by any prior experience of the seal scarer. During the following observations we conducted blind trials where the days with or without seal scarer operation were randomised. The sound head of the seal scarer was deployed in the water ~4 m below the surface once the boat anchored at the central position. An hour of observation was recorded before the blind trials began. Then, as soon as at least 5 localisations were obtained of a porpoise at a distance between 150 and 700 m of the seal scarer, the boat operator was notified via 2-way radio. The boat operator drew lots to decide whether the day was a real or a sham exposure trial, so observers on the cliff were unaware. When the seal scarer was switched on it was active continuously for 4 h, after which observations continued as long as weather and light conditions permitted.

At the beginning and at the end of each observation period, buoy positions were taken to calculate a localisation error. We analysed localisations taken from the 2 buoys at 600 and 1150 m distance from the observation point on the cliff. The standard deviation (SD) at 600 m distance was ±6 m for $x$ and ±10 m for $y$ (n = 16), while the difference between minimal and maximal localisations was 24 m for $x$ and 31 m for $y$. At 1150 m distance, SD was ±13 m for $x$ and ±12 m for $y$ (n = 16), while the difference between minimal and maximal localisations was 41 m for $x$ and 40 m for $y$. Since these measurements were randomly distributed over the day and tidal state, this therefore includes both positioning errors caused by tidal changes and inaccuracies when handling the theodolite. Tidal change in the area is minimal, with only ~30 to 50 cm difference between low and high tide. This should not lead to large variations in positioning accuracy. Even given a maximal tidal change of 50 cm, this would lead to a maximal positioning inaccuracy of ±15 m at 600 m distance and ±30 m at 1150 m distance, and is therefore within the range of localisation errors found. However, positioning errors of porpoises may be higher when the localisation had to be taken after the porpoise dove and no footprint was visible. Care was taken not to measure at great distances when the sea was not sufficiently calm to see the porpoises' footprint.

We used a Lofitech seal scarer. It emited pulses with a fundamental frequency of 14.5 kHz and a duration of ~0.55 s, with random pauses between the pulses from <1 to 90 s. Over a test period of 30 min, an overall 'on' time of 220 s was observed, which corresponds to an average duty cycle of 0.12. The time pattern and frequency spectrum of the seal scarer signal are given in Fig. 2. As can be seen from the narrowband spectrum in Fig. 2b, the signal also contains harmonics; the strongest one was the second harmonic at 29 kHz, which was ~10 dB below the level of the fundamental at a distance of 130 m. This means that the broadband level is mainly determined by the fundamental. However, the harmonics are in a frequency range where porpoise hearing is even better than at the fundamental frequency, which means that they may play a role in porpoise avoidance reactions. The sound exposure level (SEL, in dB re 1 µPa$^2$s) of the basic 0.55 s signal element is $10\log_{10}(1/0.55)$ dB or 2.6 dB lower than the short-term root mean square (rms) level. Due to the completely irregular signal structure of the seal scarer, the SELs of longer bursts are variable. From the average duty cycle of 0.12, the average SEL of a seal scarer impact of $T$ seconds is $10\log_{10}(0.12T)$ dB higher than the rms value.

In addition to the trials described above, we conducted 4 observations on 5, 6, and 25 September 2010 and 25 August 2011, when we specifically studied the responses of harbour porpoises to the seal scarer while it was deployed at distances >1 km. For this purpose, the boat operator drove the boat 1 to 4 km away from the coast. The observers asked the boat operator to switch the seal scarer on once they had spotted a porpoise within 700 m of the central buoy and had obtained at least 5 locations using the theodolite. Managing blind trials, the boat operator activated the seal scarer on all but one of the sightings during a given day and randomised the order. Before switching the seal scarer on, the boat operator made sure that no porpoise was within a 150 m radius around the boat and recorded the exact time when a trial started. The seal scarer was then left active for 5 min, and trials were separated by at least 15 min. We obtained 15 tracks with an active seal scarer and 4 tracks with an inactive seal scarer when it was between 1.3 and 3.3 km from the porpoise at the time of activation. In 2 cases, when the seal scarer was switched on, reactions could not be judged due to disturbance by a boat or the porpoise swimming into glare. Data for all other tracks are shown in Table 1.

## Sound measurements

Sound measurements of the Lofitech seal scarer were performed at several distances north, west and south of the original seal scarer deployment position. Some additional measurements were made to the northeast around the peninsula. In addition, 2 measurements were made when the seal scarer was deployed at 2 positions further offshore. These positions are identical to 2 of the positions where the seal scarer was deployed during the response study. Measurements were then made at the 2 positions where porpoises were known to react to the seal scarer deployed further offshore, using a Reson TC 4033 hydrophone, a Brüel & Kjær 2635 charge amplifier and a Tascam HD-P2 digital recorder. Calibration was performed with a G.R.A.S. 42AC piston phone with an RA0078 coupler for the TC 4033. This unit produces a 250 Hz calibration tone with a sound pressure level of 136.1 dB re 1 µPa. The recorder was set to 16 bit wave file format and a sampling fre-

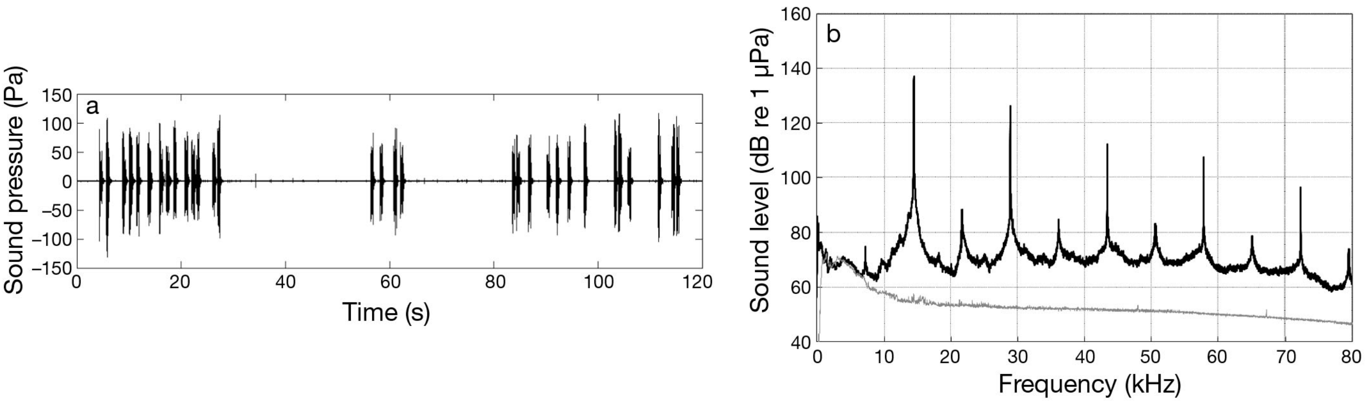

Fig. 2. (a) Typical time pattern of the seal scarer signal, observed at 130 m distance. (b) Narrowband spectrum of the Lofitech seal scarer, measured at 130 m distance. Black line: rms level of the 2-min period shown in (a). The frequency resolution is 6 Hz. Grey line: background level and/or noise limit of the instrument, measured at the same position with seal scarer switched off

Table 1. Description of the 13 tracks obtained when the seal scarer was deployed at distances beyond 1 km of the tracked harbour porpoise (calculated sound level) and the 4 baseline tracks (shaded grey). Also given are distances to the seal scarer of the last location before and during seal scarer exposure and swimming angles relative to the seal scarer for tracks where at least 3 points could be obtained after seal scarer activation. A: adult; J: juvenile

| Track | Distance (m) |  | Sound level | Mean angle (deg) |  | Porpoise |  |
|---|---|---|---|---|---|---|---|
|  | Before | After | rms (dB) | Before | During | Group | Reaction |
| 1 (off) | 751 | 779 |  | 87.2 | 112.2 | 1 A | No obvious reaction |
| 2 (on) | 1060 |  | 128 | 90.4 |  | 1 A, 1 J | Reaction (disappeared) |
| 3 (on) | 1555 | 2325 | 124 | 97.5 | 155.9 | 1 A | Reaction (avoidance) |
| 4 (on) | 1721 |  | 123 | 39.7 |  | 1 A | Reaction (disappeared) |
| 5 (on) | 1892 | 2495 | 122 | 41.4 | 144.2 | 1 A, 1 J | Reaction (avoidance) |
| 6 (on) | 2050 | 2103 | 121 | 94.6 | 98.9 | 2 A, 2 J | No obvious reaction |
| 7 (on) | 2207 | 2976 | 120 | 82.3 | 108.6 | 1 A, 1 J | Avoidance reaction? |
| 8 (off) | 2287 | 2279 |  | 130.0 | 103.6 | 1 A | No obvious reaction |
| 9 (on) | 2325 | 2848 | 119 | 54.2 | 162.2 | 2 A, 1 J | Reaction (avoidance) |
| 10 (on) | 2378 | 2853 | 119 | 62.0 | 127.7 | 1 A, 1 J | Reaction (avoidance) |
| 11 (off) | 2506 | 2378 |  | 93.1 | 62.0 | 1 A, 1 J | No obvious reaction |
| 12 (on) | 2650 | 2179 | 118 | 31.0 | 75.1 | 1 A, 1 J | No obvious reaction |
| 13 (on) | 3013 | 2754 | 116 | 64.0 | 49.0 | 1 A | No obvious reaction |
| 14 (on) | 3419 | 2973 | 116 | 50.9 | 73.3 | 1 A | No obvious reaction |
| 15 (on) | 3162 | 2718 | 116 | 101.8 | 96.0 | 1 A | No obvious reaction |
| 16 (on) | 3246 | 3289 | 115 | 104.5 | 62.9 | 1 A | No obvious reaction |
| 17 (off) | 3432 | 3518 |  | 96.5 | 87.9 | 1 A, 1 J | No obvious reaction |

quency of 192 kHz. The hydrophone was deployed at 3 m below the water surface, except at 1 very shallow position with 2 m water depth.

Prior to further processing, the recordings were high-pass filtered in order to reduce low-frequency noise caused by rolling of the boat. This was done with Adobe Audition 1.5 software, using a fourth-order Butterworth high pass with a lower limiting frequency of 3 kHz. Peak levels and rms levels of the 0.55-s-long bursts were computed by calculating the median rms level of all consecutive 125 ms time periods within 2 min of data. A threshold algorithm was used to evaluate only periods when the seal scarer was active.

To derive sound levels of the harmonic components, fast Fourier transform-based power spectra were computed with a frequency resolution of ~6 Hz and the energy in a 40 Hz wide band around the tone was summed. Finally, to obtain short-term rms values as described above, a duty cycle correction was applied by adding $10\log_{10}(120\ \mathrm{s}/T_{\mathrm{on}})$ dB, where $T_{\mathrm{on}}$ is the total 'on' time of the seal scarer within the 2 min interval.

### Statistical analyses

To analyse whether the sighting rate of harbour porpoises significantly declined during seal scarer activity, we first tested how date, hour and sea state affected the number of porpoises seen during each scan, using only data from the 9 d without seal scarer activity. We calculated a GLM fitted to a Poisson distribution, using the number of porpoises seen per scan as the response variable, and entered day, hour and sea state as linear predictor variables. To also allow for a quadratic relationship of Day and Hour, we further included $\mathrm{Day}^2$ and $\mathrm{Hour}^2$ as linear predictors. We then proceeded by backward selection until only significant terms were retained in the final model. In a second step we followed the same procedure, but only using data from days with an active seal scarer, and now also including 'seal scarer' as a factor with 3 categories (before, during and after exposure). This model was first run with all distance classes pooled, and then for each of the 3 distance classes separately.

Furthermore, we pooled the first 4 h of sighting data obtained during each of the 9 d without seal scarer activity and the 4 h when the seal scarer was active for the 7 d with an operating seal scarer. These data were then compared using a non-parametric Mann-Whitney *U*-test for 2 independent samples.

Tracking data were extracted from Cyclops and uploaded to ArcGis 9 to visualise porpoise tracks during real and sham exposures. Where locations could still be obtained after the time of seal scarer activation, tracks were split into before and during exposure with the last porpoise location before exposure marked. Distances from the seal scarer to the last porpoise location before and the last location after seal scarer start were calculated. Where at least 3 locations could be obtained after the start of the seal scarer, we also calculated swimming angles relative to the seal scarer before and during seal scarer exposure. The same was also done with the 4 tracks obtained during sham exposures.

Statistical analyses were conducted using the software R version 2.8.1 (www.r-project.org/).

## RESULTS

### Sighting rates

There was neither a significant linear ($F = 0.29$, df = 1, p = 0.59) nor quadratic ($F = 0.43$, df = 1, p = 0.51) relationship between porpoise sighting rates and date. Therefore, the variables Day and Day$^2$ were removed from the final model. Hence, there was no clear seasonal trend (neither linear nor quadratic) in the sighting data, and all days during which observations were carried out were comparable. Results from the final model, in which only significant parameters were retained, are shown in Table 2. Hour and Hour$^2$ had a significant effect on sighting rate, indicating a slight quadratic relationship, with sighting rates increasing during the morning hours and decreasing during the evening. Furthermore, sea state had an effect on the sighting rate, in that according to expectations the sighting rate decreased with increasing sea state, indicated by a significant negative linear relationship (Table 2). When the final model was run including the data collected during days when the seal scarer was active (but excluding the hours after the seal scarer was again switched off) and 'seal scarer' was included as a factor, all 4 parameters above still had a significant effect on the sighting rate of harbour porpoises (Table 2). However, 'seal scarer' explained most of the variance in the data, as seen from the $F$-value and the sum of squares value for this parameter, which were by far the highest (Table 2). This was the case when the model was run for all distances pooled and when run for each distance separately. At all distances, the effect of seal scarer was significant (0–150 m: $F = 10.4$, df = 2, $p < 0.001$; 151–450 m: $F = 34.9$, df = 2, $p < 0.001$; 451–1000 m: $F = 48.3$, df = 2, $p < 0.001$; controlling for Hour, Hour$^2$ and Sea state). In all cases, sighting rates were lower during seal scarer operation (for all distances combined, see Fig. 3).

Table 2. GLM testing the effect of the seal scarer on the sighting rates of harbour porpoises within the whole 1 km radius around the seal scarer. All data apart from the hours after seal scarer exposure are included. Dependent variable: sighting rate of harbour porpoises (porpoises per scan) at all distances (0–1000 m)

| Parameter | $b$ | SS | $F$ | df | p |
|---|---|---|---|---|---|
| Hour | 0.44 | 21.62 | 12.99 | 1 | <0.001 |
| Hour$^2$ | –0.02 | 19.87 | 11.95 | 1 | <0.001 |
| Sea state | –0.45 | 26.17 | 15.73 | 1 | <0.001 |
| Seal scarer | –4.72 | 342.22 | 205.71 | 1 | <0.001 |
| Residuals | | 1069.69 | | 643 | |

In the models calculated above, we used the unit 'porpoise sightings per scan' as the response variable. Significant effects of the variable 'seal scarer' confirmed a significant deterrence effect on harbour porpoises. The mean number of harbour porpoises seen during each scan decreased from 0.86 to 0.01 porpoises per scan, i.e. to only 1.2% of the normal sighting rate. When data were pooled into 4-h blocks, sighting rates were also significantly lower when the seal scarer was active at all distance categories ($U$-test:, 0–150 m: $Z_{7,9} = -2.56$, $p < 0.05$; 151–450 m: $Z_{7,9} = -3.17$, $p < 0.001$; 451–1000 m: $Z_{7,9} = -3.39$, $p < 0.001$) and at all distances combined ($Z_{7,9} = -3.39$, $p < 0.001$; Fig. 4), where it declined down to only 1.0% while the seal scarer was active.

During the 7 trials when the seal scarer was active (28 h in total), 2 harbour porpoises were seen during standardised scans within the 1 km radius around the seal scarer (85 and 21 min after seal scarer activation). These were both at distances of ~1000 m, right on the edge of the observation area. One was only

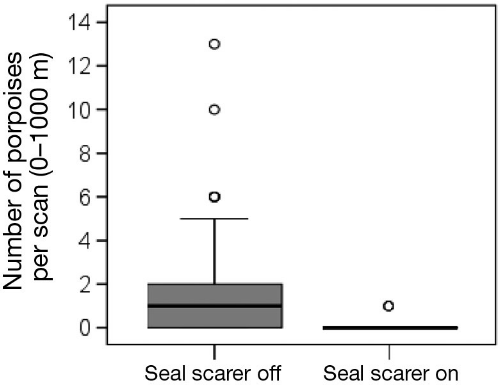

Fig. 3. Number of harbour porpoises seen during scans when the seal scarer was active and inactive for all distances combined. The difference is statistically significant. Data from times after exposure to the seal scarer are excluded. Dark band: median; box: 25% quartiles; whiskers: 25% quartiles minus outliers; circles: outliers defined as values, which are >3 box lengths from either end of the box

spotted once and could not be tracked. The other one was observed for 15 min and tracked for 11 min. It showed a closest approach distance of 798 m (track H in Fig. 5). This was the closest distance to the seal scarer at which a harbour porpoises was ever observed while the seal scarer was active. During 1 additional occasion 1 porpoise was seen between standardised scans at a distance of ~800 m, 79 min after the seal scarer was switched on (same day as the one approaching to 798 m). All 3 individuals were single adults.

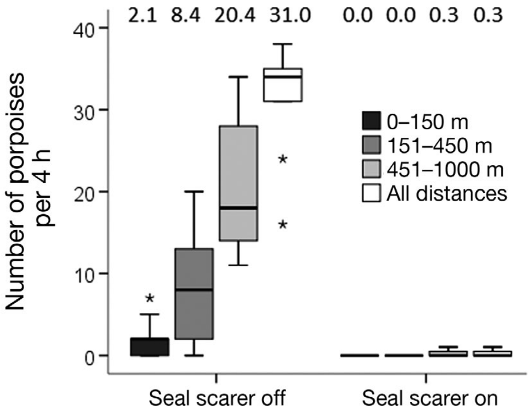

Fig. 4. Sighting rates during days when the seal scarer was off and during days when the seal scarer was on at the different distance categories and for all distances combined. Numbers at the top of the graph show the values for sighting rates in each category. Plot explanation see Fig. 3 legend

During 5 out of the 7 d with seal scarer activity, a harbour porpoise was seen between 34 and 67 min (mean 51 min) after the seal scarer was switched off. During the first 2 d, observations had to be terminated before a porpoise was seen again (84 and 35 min after the seal scarer was switched off).

### Swimming tracks

Of the 7 porpoise groups that were tracked within the 1 km radius of the seal scarer just seconds before it was switched on, 6 immediately disappeared and were not spotted again within the observation area while the seal scarer was active (Fig. 5). Only in 1 instance (track F in Fig. 5) could the porpoise be further tracked during seal scarer activity, and it swam away to the north and around the peninsula. This

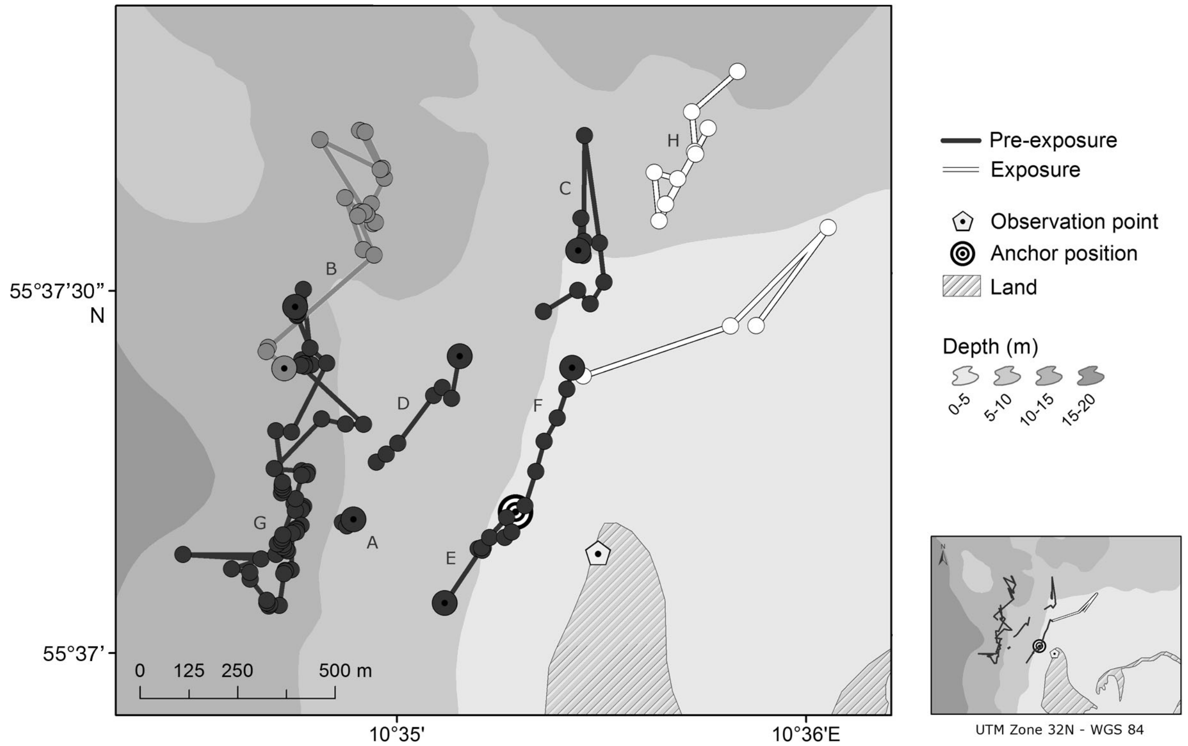

Fig. 5. Tracks of porpoises before and during seal scarer exposure. Large circles mark the last porpoise surfacing location just seconds before the seal scarer was activated. Only 1 porpoise out of 7 was seen again after the seal scarer was switched on (track F). Track H is the only other track that could be obtained during seal scarer activity; this porpoise showed the closest approach distance of 798 m. The seal scarer (black concentric circles) was positioned at the central anchoring position. Track B is shown in lighter grey to distinguish it from track G

was the same day that we later observed the closest approach distance of 798 m. The last location of all porpoises before the seal scarer was activated was obtained 0 to 55 s before sound exposure and at a distance of 300 to 700 m from the seal scarer. By contrast, during the 6 sham exposure tracks porpoises were always seen again after the theoretical time of seal scarer activation.

During 4 additional days we were able to conduct a total of 15 trials where porpoises could first be tracked without the influence of the seal scarer and then exposed to seal scarer sound at distances between 1.1 and 3.3 km and their reactions observed and judged. During 1 trial, at a distance of 1.1 km to the seal scarer, the porpoise immediately disappeared when the seal scarer was activated; during another trial at a distance of 1.7 km, the porpoise resurfaced once and was consequently lost after seal scarer activation. During 4 trials at 1.6, 1.9, 2.3 and 2.4 km, the porpoises turned after the seal scarer was switched on and swam away from the seal scarer with greater distances covered between consecutive surfacings and with greater swimming angles relative to the seal scarer than before (see an example in Fig. 6, Table 1). All these 6 cases were judged as avoidance reactions. In 1 case at a distance of 2.2 km, a mother–calf pair continued to resurface 6 times after the seal scarer was switched on, but swam away from the seal scarer around the tip of the island in a more direct movement 1 min 40 s after its activation. Because of the time delay between seal scarer activation and porpoises swimming away from it, this case was difficult to judge as it is unclear whether the individuals swam away after a delayed avoidance reaction or because of other reasons. We judged this case as a possible avoidance reaction (Table 1). In 2 cases at distances of 1.7 and 2.0 km, reactions could not be judged due to an approaching boat and porpoises swimming into glare. No reaction towards the seal scarer was found at 2.1, 2.7, 3.0, 3.2, 3.2 and 3.3 km (Table 1, Fig. 6). During the 4 baseline tracks when the seal scarer was not switched on, porpoises did not show any obvious avoidance reaction (Table 1).

### Sound measurements

Sound levels of the Lofitech seal scarer as a function of distance are depicted in Fig. 7. The estimated

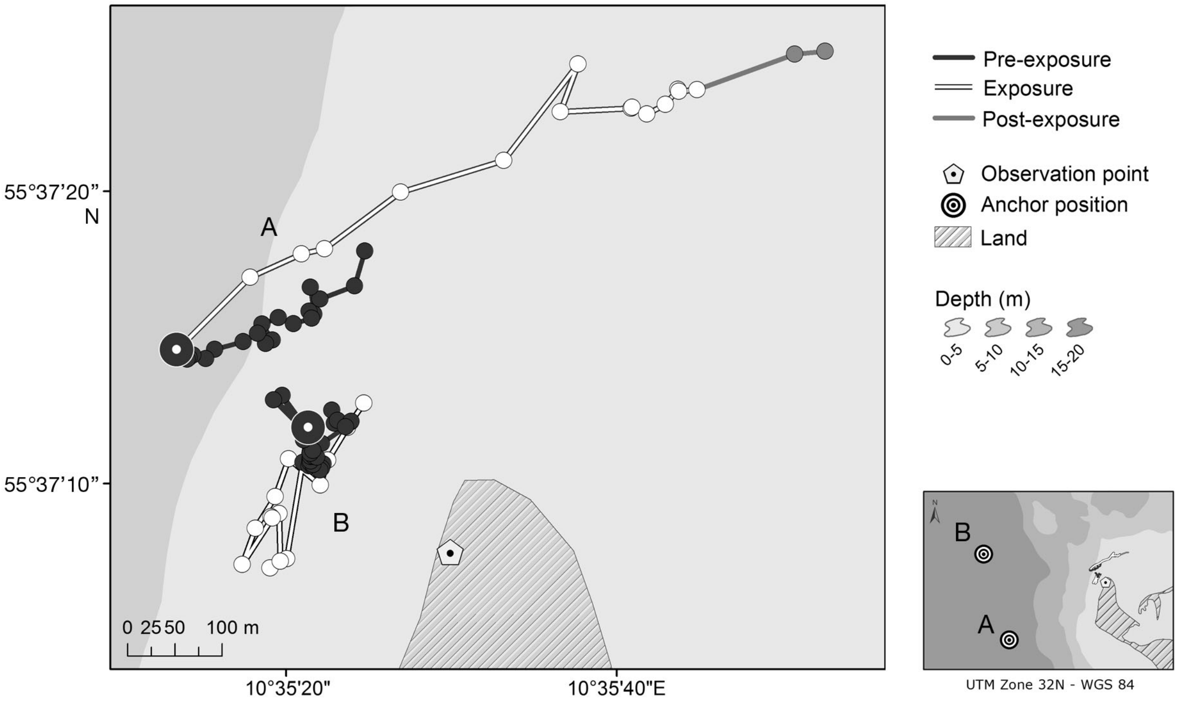

Fig. 6. Track A shows harbour porpoise track 5 (seal scarer on) as an example of a clear avoidance reaction to the seal scarer sound: the porpoise turned around and swam away from the seal scarer after its activation. Track B shows porpoise track 6 (seal scarer on), when the porpoise showed no avoidance reaction towards the seal scarer sound. The corresponding positions of the seal scarer (concentric circles) are indicated in the inset map, labelled according to the corresponding porpoise track

measurement uncertainty is ±3 dB. The level decrease with distance is significantly stronger than for spherical wave propagation without absorption or other losses and corresponds to a transmission loss of ~$27\log_{10}(d)$, where $d$ is the distance (m) between source (seal scarer) and receiver. It should be noted, however, that a simple approximation formula for the transmission loss such as $k\log d$, where k is a constant, is only valid for moderate ranges up to a few kilometers. At large distances, the sound absorption in seawater (~0.5 dB km$^{-1}$ at 10 kHz to 10 dB km$^{-1}$ at 50 kHz for a salinity of 20 ppm, which is a typical value for the Fyns Hoved area) yields an additional decrease in the sound level. However, for the distances of interest here, this decrease is negligible.

As can also be seen in Fig. 7, sound levels around the peninsula were 10 to 20 dB lower than those at the same distances further out to the sea with an unobstructed line between the seal scarer and the measurement point.

Fig. 8 shows the sould levels (rms) for the fundamental frequency component and for harmonics at some of the measurement locations, showing that transmission loss at the higher frequency components is considerable higher than at the main frequency.

## DISCUSSION

If the use of seal scarers is to be effective as a mitigation measure for harbour porpoises during offshore pile-driving activities, they have to reliably deter porpoises out of specific danger zones. Here we present results on the distance of deterrence effects of a seal scarer. Although we cannot rule out that occasional porpoises were overlooked, a clear reduction in sighting rates within a 1 km radius around the seal scarer (relating to a minimal sound level of ~129 dB re 1 $\mu Pa_{rms}$) and the fact that in most cases porpoises immediately disappeared upon exposure to the seal scarer at distances of 300 to 1100 m (relating to sound levels between 128 and 143 dB re 1 $\mu Pa_{rms}$) point to a very strong reaction at close range. That porpoises mostly could not be spotted again within the 1 km radius probably means that they left the vicinity of the seal scarer using a relatively fast movement underwater. This is in contrast to the clear but apparently slower avoidance reactions that could be observed during all instances when the seal scarer was operated at distances between 1.6 and 1.9 km (~122 to 124 dB re 1 $\mu Pa_{rms}$) and during approximately half of the cases when the seal scarer was operated at distances between 2.1 and 2.4 km (~119 to 121 dB re 1 $\mu Pa_{rms}$). Here individuals could be observed turning and swimming away from the seal scarer. At the greatest distance where avoidance reactions were observed (2.4 km), measurements revealed a sound level of 119 dB re 1 $\mu Pa_{rms}$ at the porpoises' location. With a measurement error of 3 dB during our study, this result is similar to what Kastelein et al. (2010) found when testing the responses of a captive harbour porpoise to played-back seal scarer sound at various sound levels. Differences in porpoises' reactions between studies conducted in captivity and in the field should be expected, as ambient noise levels, the porpoises' experience with sound exposure, the space over which they can move and sound transmission characteristics are different. Nevertheless, Kastelein et al. (2010) observed the porpoise to increase its distance to the sound source at a sound level of 121 dB re 1 $\mu Pa_{rms}$.

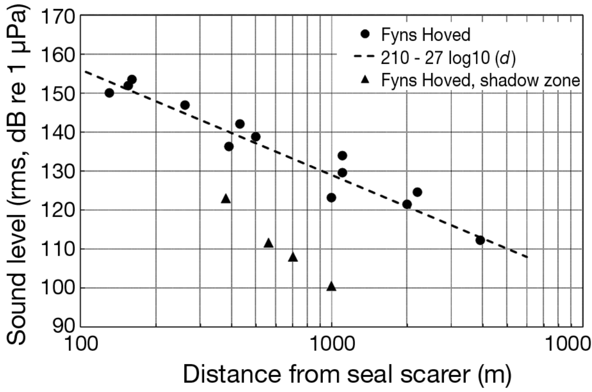

Fig. 7. Measured sound levels (rms, averaging 125 ms) of the Lofitech seal scarer signal versus distance from the seal scarer at Fyns Hoved, with an unobstructed sound travel path (●), and at an area that was shadowed by the peninsula (▲). Dashed line shows the best linear fit to the measurement points, where $d$ is the distance (m) between the seal scarer and the receiver

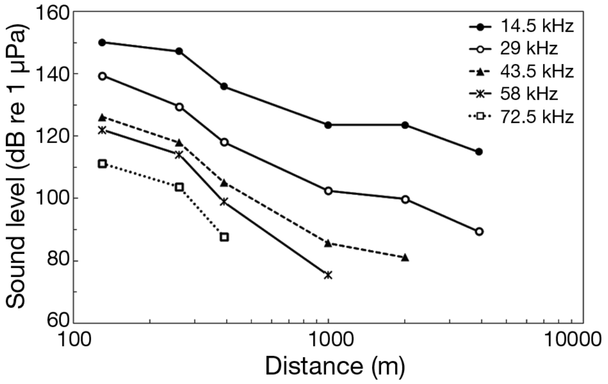

Fig. 8. Measured sound levels (rms) of the fundamental spectral component and some harmonics for some measurement positions

In 4 cases when porpoises turned around and swam away, they actually swam around the northern tip of Fyns Hoved, where, due to shadowing by the coast and shallow water, sound levels were 10 to 20 dB lower than at comparable distances further out to the sea. Porpoises thus seem to have reacted not simply by increasing their distance to the seal scarer but by deliberately seeking out quieter areas.

The transmission loss found for the seal scarer signal was higher than predicted by spherical or cylindrical spreading, which confirms findings by Shapiro et al. (2009). Transmission loss at our study location was also higher when compared with measurements in the North Sea (Brandt et al. in press), which is likely explained by the muddy sea bottom, compared with coarser sand in the North Sea, in conjunction with the shallower water depth and numerous stones and rocks that cause sound scattering. The range of audibility of the Lofitech seal scarer may therefore be substantially less at our study site and reactions at particular distances here probably translate to much larger distances elsewhere. This has to be considered when judging deterrence radii in other areas.

Furthermore, the seal scarer signal also comprised higher frequencies, where porpoise hearing is more sensitive than at the main frequency of 14.5 kHz. These high-frequency components showed a higher transmission loss than the main frequency and could play a role in porpoise avoidance reactions. These characteristics of sound transmission at different frequencies will differ between study areas and may lead to differences in the observed avoidance reactions.

Despite a clear deterrence effect of the seal scarer up to a distance of 1.9 km (some even up to 2.4 km), twice a porpoise was observed at a distance of only ~800 m, which relates to a sound level of ~132 dB re 1 $\mu Pa_{rms}$. This points to some variability in how porpoises react and may depend on the sensitivity of the individual (e.g. age, sex, prior experience) or the behavioural context of the reaction. When Kastelein et al. (2010) tested the reaction of 2 harbour seals to a seal scarer, they found them to show quite different behavioural reactions. This should also be expected for harbour porpoises. Further, reactions of 1 individual to the same stimulus may also vary between different situations. For example, the individual reaction to predation risk depends on nutritional status, reproductive status, resource availability, personality, etc. (e.g. Quinn & Cresswell 2005, Skov et al. 2011). If individuals are feeding in exceptionally good habitat they will probably be less willing to leave than when they are only travelling through.

In general, our results on porpoise reactions towards the Lofitech seal scarer seem to be quite similar to what Johnston (2002) and Olesiuk et al. (2002) found for the Airmar seal scarer. Johnston (2002) found a reduction of sighting rates up to the maximal observed distance of 1.5 km and a closest approach distance of 645 m. Olesiuk et al. (2002) concluded that there was still a significant effect up to 3.5 km distance, and a closest approach distance of only 200 m. However, distance estimates by Olesiuk et al. (2002) were rather imprecise, with a location error of ±900 m at a distance of 2000 m. Although all 3 studies agree in that an effect of a seal scarer on harbour porpoises could be proven beyond 1 km distance, comparisons have to be treated with caution as Johnston (2002) and Olesiuk et al. (2002) do not provide any information on sound levels and transmission within their study area. Our study is the first to describe harbour porpoises' reactions in the field to known sound levels of a seal scarer, and provides important information on judging the effectiveness of a seal scarer during pile-driving procedures.

Porpoises reacted immediately to the seal scarer. When they could be observed after it was switched on, they swam away at speeds between 1.3 and 3.2 m $s^{-1}$ (on average 1.6 m $s^{-1}$), and when the seal scarer was activated at a proximity <1.3 km, they may have swum even faster. With a swimming speed of 1.6 m $s^{-1}$ they could cover ~3 km in 30 min, which is above the range over which any deterrence effects were found during the conditions we studied.

It took on average 51 min (34 to 67 min) before the first porpoise was observed after the seal scarer was switched off. There is probably not a very long-lasting effect. Due to weather and daylight limitations, our observation period was unfortunately too short to determine when sighting rates returned to normal.

During the course of our study, we did not find any habituation of harbour porpoises to the seal scarer. This might not be expected for the short time period over which the experiments took place and because time periods between exposures were relatively long. However, Kastelein et al. (2010) neither did find any habituation for the 1 individual they tested with repeated exposure in captivity. In contrast, there are several studies that have shown habituation effects in seals (e.g. Götz & Janik 2010). However, during these studies, seals had a high motivation to ignore the sound of the seal scarer because they were rewarded with food. This is also described by the so-called 'dinnerbell effect' (Mate & Harvey 1986 cited in Kraus 1999): most seal scarers are used by fish farms to reduce seal depredation, and seals quickly learn to associate the otherwise unpleasant seal scarer sound with food and are attracted rather than deterred by it. The application of seal scarers during wind farm construction, however, does not pose such risks as long as porpoises have not been adapted to these devices, e.g. when they were used in fisheries within the same area. However, our results confirm previous concerns raised over the use of seal scarers in fish farms. As avoidance reactions of porpoises occur over distances of several kilometres, large-scale applications of seal scarers may lead to considerable habitat loss for harbour porpoises. To judge what deterrence range is needed in order to avoid any injury of the porpoises during pile-driving, and therefore whether the deterrence effect of the seal scarer is considered to be sufficient, more data are needed regarding the onset of permanent threshold shift (PTS) in harbour porpoises. Available data on the onset of temporal threshold shift (TTS) in harbour porpoises stem from measurements of only 1 individual (Lucke et al. 2009). The size of calculated danger zones greatly depends on its definition (e.g. TTS or PTS) and on the value considered for TTS or PTS. Furthermore, source levels of pile driving differ between projects, depending on the type of foundation and water depth. Therefore, predictions for sound emission have to be prepared and considered individually for each particular project.

Because porpoises seem to be startled when the seal scarer is activated at close range, a soft start to this device should be considered so as not to cause panic reactions in harbour porpoises, which could potentially lead to the separation of mother–calf pairs. Furthermore, the development of deterrence devices with the prime goal of deterring harbour porpoises and not seals should be considered. This might be achieved by producing devices that emit sound at a different frequencies. Kastelein et al. (2008) showed that a captive harbour porpoise avoided a pulsed 50 kHz signal down to sound levels of 108 dB re 1 µPa. This is far below 121 dB re 1 µPa$_{rms}$, the sound level at which Kastelein et al. (2010) found the porpoise to avoid the Lofitech seal scarer signal, and also 119 dB re 1 µPa$_{rms}$, a level at which we still found an avoidance reaction in the field. This points to a greater deterrence efficiency of harbour porpoises using 50 kHz signals and this option should be further investigated.

## CONCLUSIONS

Our study documents a strong deterrence effect of the Lofitech seal scarer on harbour porpoises down to sound levels of 132 dB re 1 µPa$_{rms}$ (here at 800 m distance) and incomplete deterrence effects down to sound levels of ~119 dB re 1 µPa$_{rms}$ (here at 2.4 km distance). The application of seal scarers prior to pile driving certainly reduces the risk of injury in porpoises to a great extent. However, whether the observed absolute deterrence range applies to different behavioural contexts remains difficult to judge, as porpoises may be less likely to be deterred if they are feeding in prey-rich habitats than if they are just moving through an area. Finally, the use of seal scarers as a mitigation measure should be seen as an additional, not an alternative, measure to sound mitigation. While the use of seal scarers may prevent injury in most harbour porpoises caused by pile driving, it cannot provide a complete assurance for all individuals. Furthermore, the application of seal scarers cannot mitigate the far-reaching disturbance that pile driving has been shown to cause (Tougaard et al. 2009, Brandt et al. 2011).

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## LITERATURE CITED

➤ Brandt MJ, Diederichs A, Betke K, Nehls G (2011) Responses of harbour porpoises to pile driving at the Horns Rev II offshore wind farm in the Danish North Sea. Mar Ecol Prog Ser 421:205–216

Brandt MJ, Höschle C, Diederichs A, Betke K, Nehls G (in press) Far reaching effects of a seal scarer on harbour porpoises, *Phocoena phocoena*. Aquat Conserv: Mar Freshw Ecosyst

➤ Carlström J, Berggren P, Tregenza NJC (2009) Spatial and temporal impact of pingers on porpoises. Can J Fish Aquat Sci 66:72–82

Cox TM, Read AJ, Solow A, Tregenza N (2001) Will harbour porpoises (*Phocoena phocoena*) habituate to pingers? J Cetacean Res Manag 3:81–86

➤ Culik BM, Koschinski S, Tregenza N, Ellis GM (2001) Reactions of harbor porpoises *Phocoena phocoena* and herring *Clupea harengus* to acoustic alarms. Mar Ecol Prog Ser 211:255–260

➤ Götz T, Janik VM (2010) Aversiveness of sounds in phocid seals: psycho-physiological factors, learning prcesses and motivation. J Exp Biol 213:1536–1548

➤ Johnston DW (2002) The effect of acoustic harassment devices on harbour porpoises (*Phocoena phocoena*) in the Bay of Fundy, Canada. Biol Conserv 108:113–118

Kastelein RA, Wensveen PJ, Hoek L, Verboom C, Terhune W, Hille JM, Lambers R (2008) Underwater hearing sensitivity of harbour seals for tonal signals and noise bands. IMARES, Wageningen

Kastelein RA, Hoek L, Jennings N, Jong CD, Terhune J, Dieleman M (2010) Acoustic mitigation devices (AMDs) to deter marine mammals from pile driving areas at sea: audibility and behavioural responses of a harbour porpoise and harbour seals. COWRIE Ref: SEAMAMD-09, Technical Report 31st July 2010

Koschinski S, Culik BM, Henriksen OD, Tregrenza N, Ellis G, Jansen C, Kathe G (2003) Behavioural reactions of free-ranging porpoises and seals to the noise of a simulated 2 MW windpower generator. Mar Ecol Prog Ser 265:263–273

Kraus SD (1999) The once and future ping: challenges for the use of acoustic deterrents in fisheries. Mar Technol Soc J 33:90–93

Kyhn LA, Tougaard J, Thomas L, Rosager Duve L and others (2012) From echolocation clicks to animal density — acoustic sampling of harbour porpoises with static dataloggers. J Acoust Soc Am 131:550–560

Lucke K, Siebert U, Lepper PA, Blanchet MA (2009) Temporary shift in masked hearing thresholds in a harbour porpoise (*Phocoena phocoena*) after exposure to seismic airgun stimuli. J Acoust Soc Am 125:4060–4070

Madsen PT, Wahlberg M, Tougaard J, Lucke K, Tyack P (2006) Wind turbine underwater noise and marine mammals: implications of current knowledge and data needs. Mar Ecol Prog Ser 309:279–295

Morton AB, Symonds HK (2002) Displacement of *Orcinus orca* (L.) by high amplitude sound in British Columbia, Canada. ICES J Mar Sci 59:71–80

Olesiuk PF, Nichol LM, Sowden MJ, Ford JKB (2002) Effect of the sound generated by an acoustic harassment device on the relative abundance and distribution of harbour porpoises (*Phocoena phocoena*) in retreat passage, British Columbia. Mar Mamm Sci 18:843–862

Petersen P (1927) Zur Bestimmung der Windstärke auf See. Für Segler, Dampfer und Luftfahrzeuge. Ann Hydrogr Marit Meteorol 55:69–72

Quinn JL, Cresswell W (2005) Escape response delays in wintering redshank, *Tringa totanus*, flocks: perceptual limits and economic decisions. Anim Behav 69:1285–1292

Reid JB, Evans PGH, Northridge SP (2003) Atlas of cetacean distribution in north-west European waters. Joint Nature Conservation Committee, Peterborough

Shapiro AD, Tougaard J, Jørgensen PB, Kyhn LA and others (2009) Transmission loss patterns from acoustic harassment and deterrent devices do not always follow geometrical spreading predictions. Mar Mamm Sci 25: 53–67

Skov C, Baktoft H, Brodersen J, Brönmark C, Chapman BB, Hansson LA, Nilsson PA (2011) Sizing up your enemy: individual predation vulnerability predicts migratory probability. Proc Biol Sci 278:1414–1418

Southall BL, Bowles AE, Ellison WT, Finneran JJ and others (2007) Marine mammal noise exposure criteria: initial scientific recommendations. Aquat Mamm 33:411–522

Tougaard J, Carstensen J, Teilmann J (2009) Pile driving zone of responsiveness extends beyond 20 km for harbour porpoises (*Phocoena phocoena*, (L.)). J Acoust Soc Am 126:11–14

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