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Behavioural reactions of free-ranging porpoises and seals to the noise of a simulated 2 MW windpower generator

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ABSTRACT: Operational underwater noise emitted at 8 m s^{-1} by a 550 kW WindWorld wind-turbine was recorded from the sea and modified to simulate a 2 MW wind-turbine. The sound was replayed from an audio CD through a car CD-player and a J-13 transducer. The maximum sound energy was emitted between 30 and 800 Hz with peak source levels of 128 dB (re 1 μPa^2 Hz^{-1} at 1 m) at 80 and 160 Hz (1/3-octave centre frequencies). This simulated 2 MW wind-turbine noise was played back on calm days (<1 Beaufort) to free-ranging harbour porpoises *Phocoena phocoena* and harbour seals *Phoca vitulina* in Fortune Channel, Vancouver Island, Canada. Swimming tracks of porpoises and surfacings of seals were recorded with an electronic theodolite situated on a clifftop 14 m above sea level. Echolocation activity of harbour porpoises close to the sound source was recorded simultaneously via an electronic click detector placed below the transducer. In total we tracked 375 porpoise groups and 157 seals during play-back experiments, and 380 porpoise groups and 141 surfacing seals during controls. Both species showed a distinct reaction to wind-turbine noise. Surfacings in harbour seals were recorded at larger distances from the sound source (median = 284 vs 239 m during controls; $p = 0.008$, Kolmogorov-Smirnov test) and closest approaches increased from a median of 120 to 182 m ($p < 0.001$) in harbour porpoises. Furthermore, the number of time intervals during which porpoise echolocation clicks were detected increased by a factor of 2 when the sound source was active (19.6% of all 1 min intervals as opposed to 8.4% of all intervals during controls; $p < 0.001$).These results show that harbour porpoises and harbour seals are able to detect the low-frequency sound generated by offshore wind-turbines. Controlled exposure experiments such as the one described here are a first step to assess the impact on marine mammals of the new offshore wind-turbine industry.

KEY WORDS: Harbour porpoise · *Phocoena phocoena* · Harbour seal · *Phoca vitulina* · Noise · Offshore windpower · Environmental assessment

INTRODUCTION

Offshore windpower plants (also widely known as wind farms) are being built world-wide in coastal waters, and many of the affected areas are inhabited by marine mammals. In the German Exclusive Economic Zone (beyond 12 n miles offshore) of the Baltic and North seas, various power companies have applied for building permits for 30 large wind farms with a possible capacity of over 60 GW (Federal Maritime and Hydrographic Agency pers. comm.). If all these wind farms were realised, this would comprise 12000 wind-turbines, each of 5 MW capacity (of which only prototypes exist to date), or 30000 wind-turbines

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of the 2 MW class. The area needed for an industrial development of this magnitude would be 13 000 km^2. However, many of the areas designated for offshore wind farms are in densely populated harbour seal and harbour porpoise areas (Reijnders et al. 1997, Dietz et al. 2000, Orthmann 2000, Hammond et al. 2002).

Marine mammals are known to be sensitive to anthropogenic noise (Richardson et al. 1995). During the past 100 yr, noise from human activities has significantly increased in the marine environment; especially low-frequency components from shipping and other anthropogenic sources, dominate in many coastal areas (Urick 1986, cited in Kastak & Schusterman 1998). High-intensity low-frequency sounds propagate over long ranges (Urick 1967). The effects of possible biological significance can be masking of echolocation sounds or calls from conspecifics, predators or prey (Southall et al. 2000), disturbance of natural behaviour (NRC 1994), hearing damage or physiological stress (NRC 1994, Richardson 1997, Hofer & East 1998).

During construction and operation of wind-turbines, low-frequency noise is emitted into the water (Degn 2000, Maxon 2000, Henriksen 2001). Recent studies indicate that seals and harbour porpoises can hear sound in the frequency range typical for these operations (Kastak & Schusterman 1998, Kastelein et al. 2002). The extent and pattern of sound radiation of wind-turbine operation noise remains largely unknown. However, from experiments with different pingers operating at similar source levels but different frequencies, it is known that free-ranging harbour porpoises leave the area around such artificial sound sources (Koschinski & Culik 1997, Culik et al. 2001).

The controlled exposure experiment described here is the first practical attempt to assess the influence of the operational noise of offshore wind-turbines on the behaviour of free-ranging harbour porpoises and harbour seals. Since it is very difficult to record the behaviour of marine mammals in windy areas where offshore wind farms are being built, we simulated the sound of a wind-turbine in an area with extremely good sighting conditions (i.e. sufficient animal density, calm protected waters, low background noise and a vantage point on a cliff top). We recorded the swimming behaviour of harbour seals and harbour porpoises with respect to the artificial sound source, as well as echolocation behaviour of harbour porpoises.

MATERIALS AND METHODS

Study site. From 26 June to 17 July 2001, we conducted behavioural observations on harbour porpoises and harbour seals in Fortune Channel (49° 11′ N, 125° 46.5′ W), Vancouver Island, British Columbia, Canada. The fjord-like area offered calm protected conditions at Beaufort 0 for 3 to 8 h d^{-1}. These were perfect conditions for tracking the positions of the marine mammals (Koschinski & Culik 1997, Culik et al. 2001). Boat traffic in the area is very rare, with a maximum of 5 small outboard-powered boats per day.

Sound recording and simulation. Operational noise emitted at 8 m s^{-1} by a 550 kW WindWorld wind-turbine on monopile foundation situated off the coast of the Swedish island Gotland was recorded from the sea via a DAT tape recorder, 20 m from the foundation of the wind-turbine (Degn 2000). The noise measurements were originally measured as sound pressure density spectrum levels (in dB re 1 µPa^2 Hz^{-1}) in ⅓-octaves. This expresses that the total noise level in each ⅓-octave is measured as dB re 1 µPa^2, and afterwards is divided by the width of each ⅓-octave band.

For use in this experiment, the original recording was modified in an acoustics lab (using Cool Edit Pro 1.0) to simulate a 2 MW offshore wind-turbine, as calculated from onshore generator data by Degn (2000) (Fig. 1). Since we used a point source for underwater sound transmission (see last paragraph, this section), spherical spreading was assumed for the first 20 m of sound radiation, and received levels at 20 m from the foundations were recalculated to source levels by adding 26 dB.

This simulated 2 MW wind-turbine sound was recorded on an audio-CD and replayed via a car CD player (Blaupunkt 'Kiel') and a low frequency underwater transducer (J-13, Chesapeake Technology). Frequency analysis of the replayed sound took place at

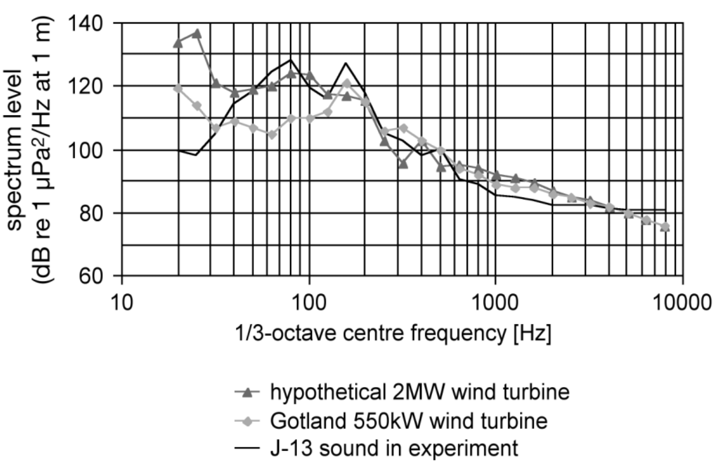

Fig. 1. Frequency analysis of the sound (dB re 1 µPa^2 Hz^{-1} at 1 m, centre frequencies of ⅓-octave bands) recorded from a 550 kW WindWorld wind-turbine (light grey) and calculation of the frequency distribution of a potential 2 MW offshore wind-turbine (dark grey; both recalculated after Degn 2000, see text above). The black curve shows the sound levels used to ensonify marine mammals in this study

the measuring platform of the Bundeswehr Technical Centre for Ships and Naval Weapons in Lake Plön (Germany). The J-13 was submerged at 5 m depth and 1 m distance from a calibrated hydrophone (B&K 8101). Further equipment used for this procedure was an amplifier (B&K 2636) and a frequency analyser (B&K 3550).

The main sound energy of the recording was emitted between 30 and 800 Hz, with peak source levels of 128 dB (re 1 $\mu Pa^2 Hz^{-1}$ at 1 m) at 80 and 160 Hz (centre frequencies of ⅓-octave bands). Sound peaks below 30 Hz measured at sea in the Swedish wind farm could not be generated by the transducer used in the field experiment.

In the field, the car CD player was powered by a 12 V battery, both housed in a waterproof bin (Ø 46 cm, height 56 cm) and anchored at a water depth of 35 m (Fig. 2). The underwater transducer (J-13) was connected to the CD player and kept at 4 m depth by a float (Ø 65 cm). The horizontal distance to the bin was 1.5 m.

Note that in the field, the sound radiation properties of a point source, such as the J-13 transducer, differ from the radiation properties of a vibrating cylindrical pipe extending through the whole water column, such as the monopile of an offshore wind-turbine. It can be assumed that sound from a point source spreads spherically until sound waves reach the surface and the bottom and then spreads more or less cylindrically. For the monopile, cylindrical spreading can be assumed throughout. At a water depth of 35 m, such as in the experiment, spreading only differs during the first 17.5 m. Beyond that range spreading can be assumed to be cylindrical.

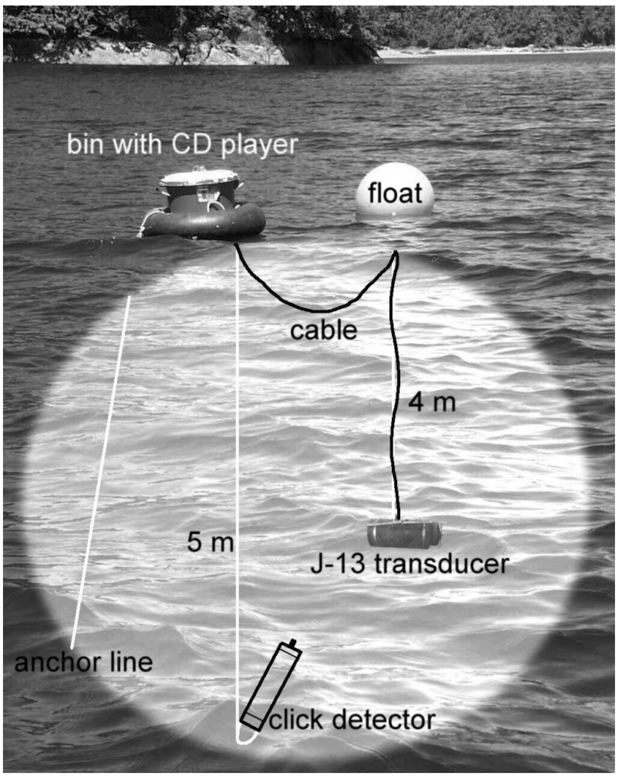

Fig. 2. Experimental field set-up for the controlled exposure experiment in Fortune Channel (see text above for details)

Logging of harbour porpoise echolocation activity. In order to detect the presence of harbour porpoises day-round, a click detector (Chelonia TPOD1 configured to detect 130 kHz narrow-band echolocation clicks in trains from porpoises, cf. Cox et al. 2001) was positioned below the transducer (Fig. 2). The detector is self-contained and automatically logs the start and finish of each porpoise click to 10 µs resolution when the device is adjusted to pulse frequencies of 130 kHz (details available at www.chelonia.demon.co.uk/).

Click and sightings data were matched as follows: If one or more surfacings were recorded within 2 min of a logged click, the co-ordinates of the surfacing point closest to the time of the click was assigned to it. This procedure was only possible when not more than 1 porpoise group was in the observation area.

Theodolite-tracking of harbour porpoises. The theodolite (GDM 608-S, Trimble Navigation) was positioned on a cliff, ca. 14 m above sea level overlooking an area of approximately 600 × 2000 m. However, we mainly focused our attention on the vicinity of the transducer in order to determine the minimum distance of the surfacing mammals. The theodolite was used to obtain horizontal and vertical angles as well as the time (to the nearest second) of each surfacing of harbour porpoise groups or individual harbour seals. In porpoise groups we tracked the leading animal whenever possible. Theodolite elevation above sea level was obtained approximately every 30 min by measuring the angle of the water surface at a plumb line attached above sea level on the opposite shore of the fjord. The distance to a mirror on the top of the plumb line was measured using the built-in laser distance-meter. Theodolite elevation above sea level was linearly interpolated between recording intervals. The plumb line also served as reference point (angle 0°) for measurements of the horizontal angle of sightings. The accurate position of surfacing animals could readily be calculated from theodolite data of elevation above sea level and horizontal and vertical angles of surfacings using trigonometric equations. Instrument accuracy suggests that the range error of sightings was less than 3 m at maximum range, while azimuth error was less than 50 cm. The coast-line as well as the position of the sound source were also recorded using this procedure.

Due to tidal currents, the position of the transducer and click detector were not constant. These were recorded at fixed intervals and interpolated. From position data we obtained minimum distances to the sound source for individual porpoise groups. Because only the movements of a few seals could be followed over time, all seal surfacings were recorded and used for analysis.

During 4 d (total of 20:57 h) of experiments with replayed wind-turbine sound, we tracked 375 porpoise groups during 2690 surfacings. During 5 d (22:43 h) of control observations (no replayed sound) we tracked 380 porpoise groups during 2780 surfacings. In total, 38 of all groups contained calves. 'Groups' consisted either of single animals or a number of animals swimming temporarily close together. Some individually marked animals helped in identification of groups when more than 1 group used the observation area at a time. When the composition of such a group changed, we defined it as a new group. Group size varied from 1 to 12 individuals. We found no significant difference in group-size between control and wind-turbine sound sessions ($\text{median}_{\text{control}}$ and $\text{median}_{\text{wind-turbine}} = 2$; $p > 0.05$).

RESULTS

Harbour porpoises

Individual groups were observed for as long as possible. Observation duration ranged from 3 s to 95 min. We found no significant difference in observation time between wind-turbine sound and control sessions (i.e. animals were neither attracted to nor deterred from the general area). The median observation duration during control periods was 3:01 min whereas the median during replay periods was 3:13 min ($p > 0.05$).

Fig. 3 shows the closest observed surfacings of all harbour porpoise groups in relation to the sound source. The comparison of surfacing distributions (Fig. 4) yields that the closest observed approaches to the transducer were significantly nearer in control situations (median of 120 m without sound) than during wind-turbine sound sessions (182 m; $p < 0.001$, Kolmogorov-Smirnov test). The absolute minimum distance also increased from 0.7 m during controls to 4.5 m during play-back.

In order to obtain a better resolution of the effect observed, we determined surfacing distance from the sound source within different shells (0–60, 60–120 m, and so on). Within the 0 to 60 m shell, the difference in approach behaviour between control and sound periods was significant ($\text{median}_{\text{control}} = 29.8$ m; $n = 104$; $\text{median}_{\text{wind-turbine}} = 36.2$ m; $n = 84$; $p = 0.04$; Kolmogorov-Smirnov test). At greater distances from the sound source, no significant shift in approach distance could be observed (shell radius 60–120 m: $p = 0.97$;

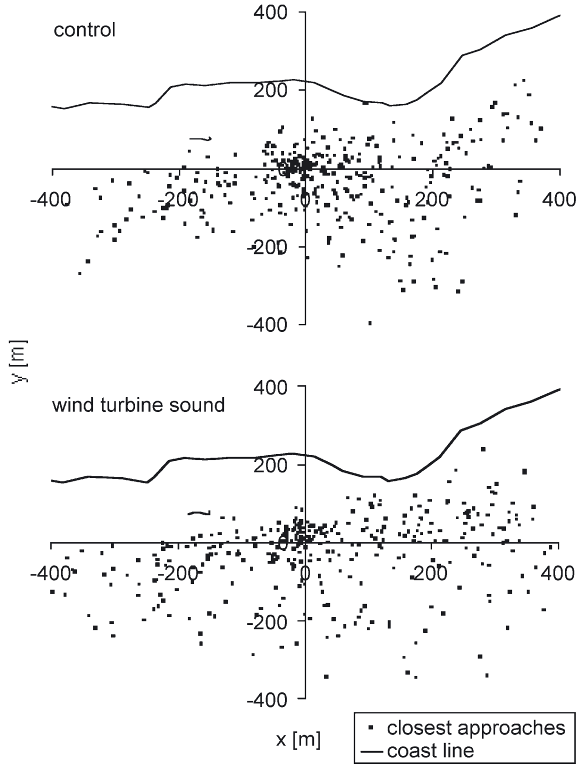

Fig. 3. *Phocoena phocoena.* Closest observed surfacings (m) of all groups in relation to the sound source (middle of graph)

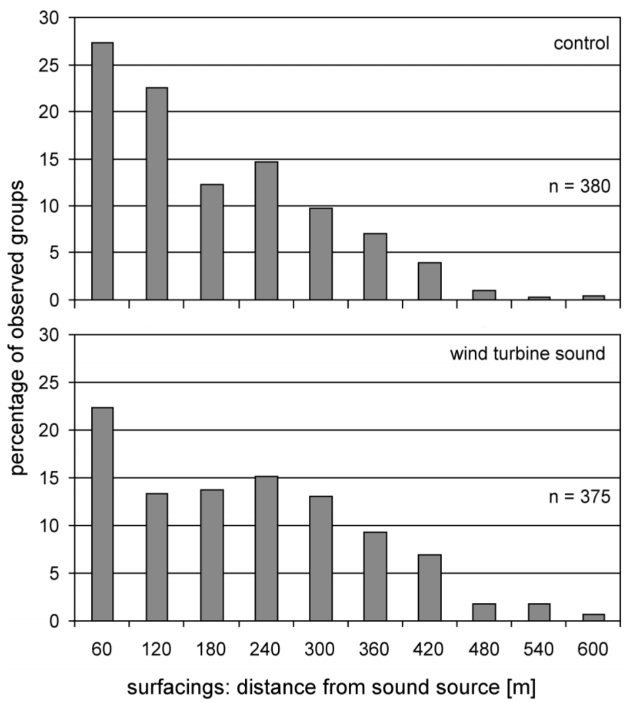

Fig. 4. *Phocoena phocoena.* Distribution (%) of the closest observed approaches of groups to the sound source. During wind-turbine sound sessions, porpoises maintained a larger distance to the transducer than during control sessions (distribution shifted to the right)

radius 120–180 m: $p = 0.87$; radius 180–240 m: $p = 0.67$; radius 240–300 m: $p = 0.54$; Kolmogorov-Smirnov test).

During the observations, we also recorded the echolocation clicks of harbour porpoises. Fig. 5 shows that peaks in echolocation activity (expressed as clicks min^{-1}) coincide with sightings in the vicinity (in the given example within a 60 m radius) around the click detector. Multiple regression analysis (all data pooled) yields that click frequency (clicks min^{-1}) is not correlated with group size ($p = 0.868$) but with distance ($p < 0.001$). A linear correlation with distance yields an adjusted $r^2 = 0.037$ ($p < 0.001$; $n = 304$):

$$\text{Clicks } (\text{min}^{-1}) = 34 - 0.2 \text{ distance (m)} \qquad (1)$$

This correlation entails that when harbour porpoises are more distant than 170 m, no clicks are received by the detector. This is confirmed by the fact that 98% of all sightings corresponded to a click-detection within a 150 m range.

Interestingly, harbour porpoises used their sonar more often during periods of replayed wind-turbine sound than during control situations (Fig. 6). In the control situation (no turbine sound) clicks were recorded during 8.4% (88 min) of all logged minute intervals (1037 min), whereas during wind-turbine sound, clicks were recorded during 19.6% (247 min) of the minute intervals logged by the detector (1257 min) ($p < 0.001$; Kolmogorov-Smirnov test). This is in contrast to the larger median approach distance recorded during periods of active sound because detection probability decreases with distance.

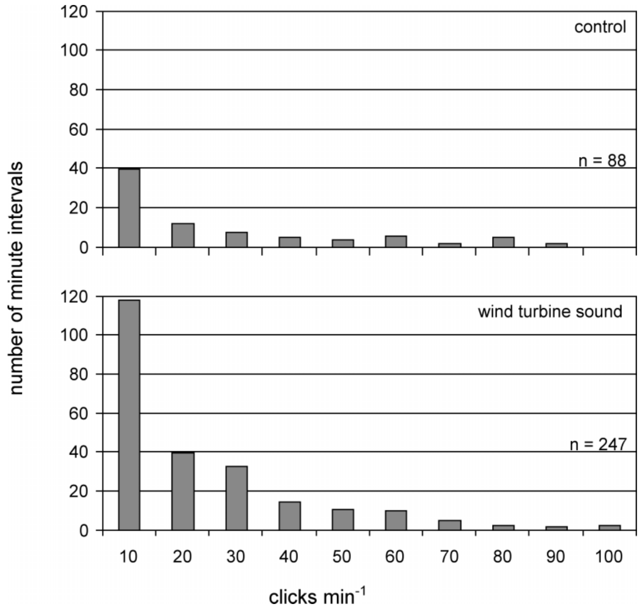

Fig. 6. *Phocoena phocoena*. Click distribution (n): during controls, clicks were only recorded during 8.5% of all 1037 min intervals, whereas during wind-turbine sound, clicks were recorded during 19.6% of the 1257 min intervals ($p < 0.001$; Kolmogorov-Smirnov test)

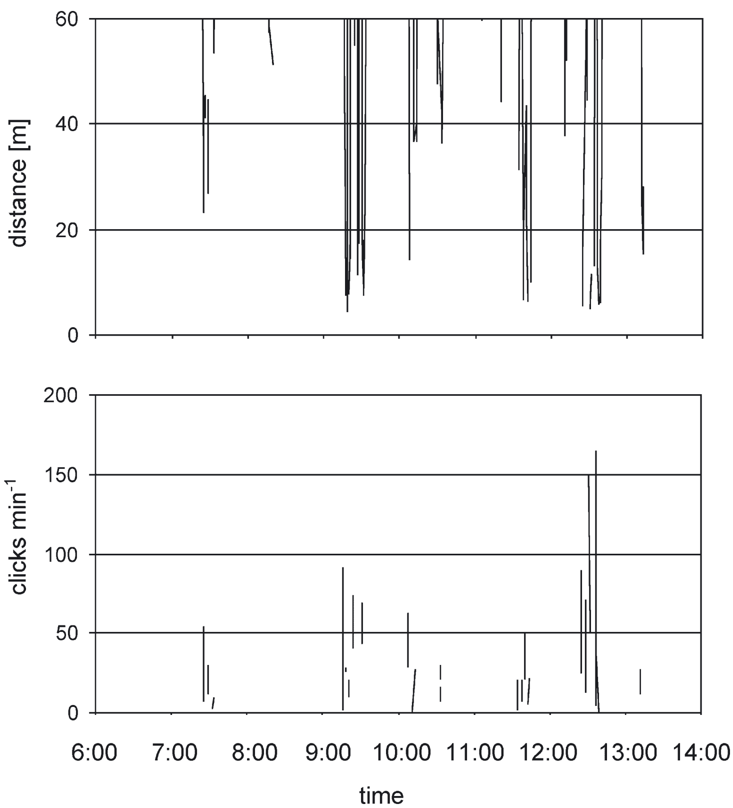

Fig. 5. *Phocoena phocoena.* Match of harbour porpoise echolocation clicks (bottom graph) and sighting distance (top graph) within a 60 m radius of the sound source

However, the difference between the median number of clicks min^{-1} in both parts of the experiment was not significant ($median_{control} = 16.5$ clicks min^{-1}, $median_{wind\text{-}turbine} = 12$ clicks min^{-1}; $maximum_{control} = 193$ min^{-1}; $maximum_{wind\text{-}turbine} = 174$ min^{-1}; $p > 0.05$, Kolmogorov-Smirnov test).

Harbour seals

During 4 sessions with wind-turbine sound we tracked 157 seals. In 5 control sessions (without sound) we recorded 141 surfacing seals (Fig. 7). Groups consisted mostly of 1 individual, and during rare occasions groups had 3 members (group size: $median_{control}$ and $median_{wind\text{-}turbine} = 1$; $p > 0.05$; Kolmogorov-Smirnov test). At least 1 repeatedly observed female had a pup. A haul-out site was situated just outside the observation area.

During periods of replayed wind-turbine sound, the distance of seal surfacings from the sound source increased significantly (Fig. 8) compared to the control situation without replayed sound ($median_{wind\text{-}turbine}$ =

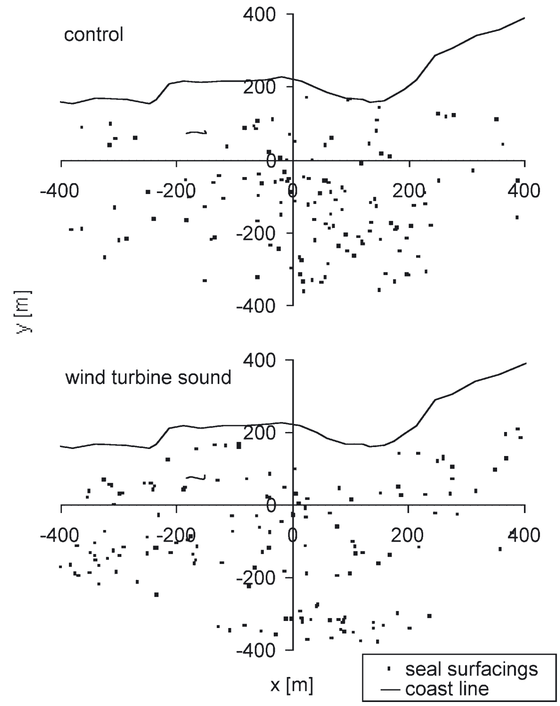

Fig. 7. *Phoca vitulina.* Comparison of all surfacings during control and sound periods in relation to the sound source (located at the origin)

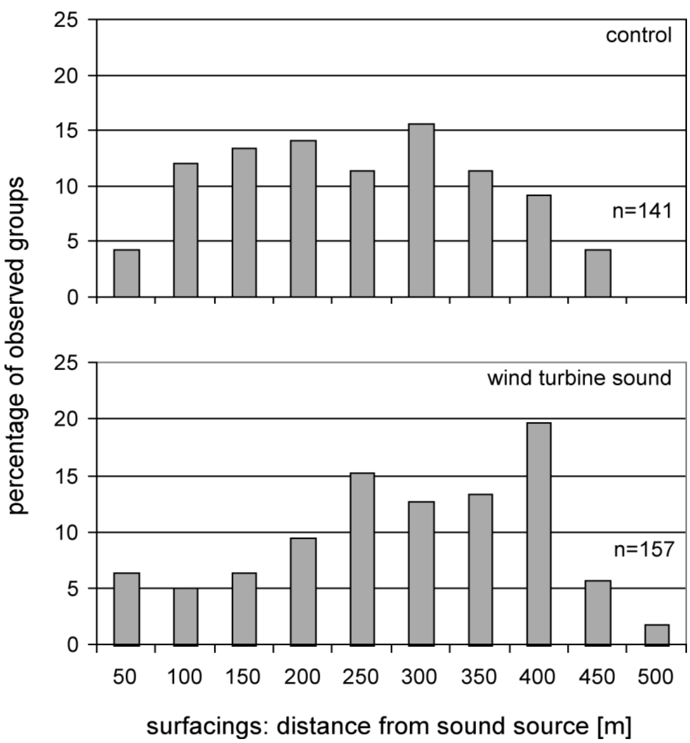

Fig 8. *Phoca vitulina.* Distribution (%) of surfacings in relation to the sound source. During periods of replayed sound, harbour seal surfacings were shifted away from the sound source

284 m; $median_{control}$ = 239 m; $p = 0.008$, Kolmogorov-Smirnov test). The closest approach of a seal during control sessions was 9.6 m, whereas the closest approach during sound periods was 12.0 m.

DISCUSSION

Harbour porpoises

Harbour porpoises showed a distinct reaction to the wind-turbine sound during the experiment: closest approaches of porpoise groups increased markedly during sound periods, and echolocation activity was also extended. However, no schooling (i.e. animals swimming very close together) or fast swimming were observed, which in former studies using gillnet pingers was taken as evidence for a fright reaction (Kastelein et al. 1995, Koschinski & Culik 1997). Furthermore, avoidance behaviour was less intensive than in a pinger experiment where an exclusion zone was observed (Culik et al. 2001). Single groups approached the active sound source as close as 4.5 m. Duration of porpoise presence in the observation area did not differ between treatments and controls. From these observations it can be concluded that (1) harbour porpoises are able to hear the wind-turbine sound played from the CD, (2) animals seemed to be cautious when confronted with this new acoustic stimulus, and (3) porpoises explored the active sound source with their biosonar.

Hearing

Hearing abilities of harbour porpoises have so far been investigated in only a few studies. An early audiogram of a harbour porpoise (Andersen 1970) did not consider frequencies below 1 kHz. However, these frequencies are the most important to assess the influence of wind-turbine sound on marine mammals (cf. Degn 2000). In a recent study, Kastelein et al. (2002) observed reactions of a trained harbour porpoise to a 500 Hz signal at a received level of 89 to 96 dB (re 1 µPa) and to a 250 Hz signal at a level of 112 to 118 dB. The wind-turbine sound played back in this experiment reached a source level of 128 dB (re 1 $\mu Pa^2 Hz^{-1}$ at 1 m) at 80 and 160 Hz (see Fig. 1 for frequency spectrum). Thus, the source level of off-shore wind-turbines is above the hearing threshold of harbour porpoises at those frequencies. The porpoises' hearing range depends on sound radiation.

At this time no realistic assumption for sound radiation of wind-turbine noise exists. A simplified model for sound radiation in this experiment can be taken from Kastak & Schusterman (1998). They assume a 'lossy' cylindrical spreading of low-frequency point sources, such as the transducer used in this experiment (assumed transmission loss = 15 log$R$; where R = distance from sound source in m) following a spherical spreading (transmission loss = 20 log$R$) from the source to bottom and surface. This model can be described by the following equation:

$$L_R = L_{1m} - 20\log R_1 - 15\log(R/R_1) \quad (2)$$

where L_R = received level (dB re 1 µPa) at a distance R from the sound source; L_{1m} = source level (dB re 1 µPa at 1 m); and R_1 = distance at which the spherical wave transforms into a cylindrical wave (in this study it was approximately 20 m).

The strongest noise from the simulated wind-turbine (128 dB at 160 Hz) is about 16 dB above the hearing threshold of a harbour porpoise (112 dB measured at 250 Hz; Kastelein et al. 2002). According to Eq. (2) this component of the spectrum will be reduced to the hearing threshold level at a range of 6.3 m.

This is in contrast to the 60 m shell in which the observed shift from the sound source was strongest. A narrow reception beam — which has been found experimentally in dolphins for 30, 60 and 120 kHz (Au 1993) and increases hearing abilities in the forward direction — can be dismissed in harbour porpoises for low-frequency sound (Taylor et al. 2001, R. A. Kastelein pers. comm.). However, by correcting wind-turbine broad-band noise to sound conditions used in controlled auditory experiments (narrow band signals), Henriksen (2001) calculated the possible hearing distance of a harbour porpoise to the loudest components of a small offshore wind-turbine to be 40 m, assuming cylindrical spreading. This corresponds better with the avoidance reaction seen here in the 60 m shell around the transducer.

A problem with existing audiograms is that they derive from studies with only 1 individual. Their results are thus dependent of its motivation, health, and age, as well as other factors. The porpoise studied by Kastelein et al. (2002) was stranded as a juvenile on the Dutch coast and had been living in a small concrete pool for a considerable time. It is possible that the hearing thresholds are lower in free-living conspecifics. Also, some of the study animals may have reacted to higher frequencies perceived from the wind-turbine sound spectrum. Sound radiation from the transducer at higher frequencies was weaker, but the hearing threshold of harbour porpoises is also lower above 1 kHz.

Avoidance of sound stimulus

Investigations of behavioural responses of marine mammals to disturbing sounds mainly derive from studies testing acoustic deterrent (ADDs) or harassment devices (AHDs) used in fisheries or aquaculture (e.g. Cox et al. 2001, Culik et al. 2001, Johnston 2002, Olesiuk et al. 2002). As opposed to the low-frequency noise produced by offshore wind-turbines, their main energy is radiated at frequencies between 10 and 25 kHz, with source levels of 130 to 145 dB (re 1 µPa at 1 m) in ADDs and up to 200 dB in AHDs (e.g. Jefferson & Curry 1994). Some devices even produce sound sweeps to frequencies as high as 160 kHz (Goodson 1997).

Behavioural reactions of harbour porpoises to these or similar disturbing sounds observed in laboratory or field experiments were schooling (Dudok van Heel 1962, Kastelein et al. 1995, Koschinski & Culik 1997), fast swimming (Kastelein et al. 1995, 1997), increased surfacing rate (Kastelein et al. 1997, 2000) and avoidance by staying in the distant area of their pool or net enclosure (Kastelein et al. 1995, 1997, 2000).

Since our earlier studies with ADDs were conducted in the same area using a similar method, we can compare harbour porpoise reactions to both noise sources. When exposed to ADDs, porpoises showed a strong aversive behaviour. Koschinski & Culik (1997) found a mean closest approach distance of 133 m to a 2.9 kHz ADD with a source level of 115 dB (re 1 µPa at 1 m, as opposed to 34 m in the control). The median approach distance to another ADD (20 to 160 kHz) with a level of 145 dB increased from 150 m in controls to 530 m during pinger deployment (Culik et al. 2001). Also, when Olesiuk et al. (2002) used an AHD (10 kHz; 194 dB) they even found a habitat displacement of 90% by harbour porpoises from an area with a radius of 3.5 km. This shows that displacement is a function of sound level.

When playing back wind-turbine noise, the avoidance reaction was much weaker and we observed no exclusion zone. Median observed closest approaches were 182 m during sound periods, as opposed to 120 m during controls, but some porpoises approached much closer.

Exploratory behaviour and echolocation activity

Cox et al. (2001) recorded a significantly reduced echolocation rate of harbour porpoises when an ADD was activated. This may have been due to a limited range of the click detector and increased distance of the animals, or because the porpoises aimed their strongly directional sonar beam away from the ADD, or to the fact that they reduced their echolocation activity. By comparison, Hector's dolphins *Cephalorhynchus hectori* did not change their echolocation behaviour significantly when exposed to 3 different types of ADDs (Stone et al. 2000). Furthermore, only

5.4 to 55.3% of Hector's dolphins showed avoidance behaviour, compared to 92.4% in a study on harbour porpoises (Koschinski & Culik 1997). It can be assumed that different odontocete species perceive, interpret and react differently to anthropogenic noise.

Reaction to a sound stimulus is not necessarily expressed by aversion. The typical response to a novel sound may also result in exploration. The 2-fold increase in echolocation activity we found here is evidence for such an effect of wind-turbine sound on porpoise behaviour. As opposed to this, ADD sound is presumably perceived as a threat.

Echolocation clicks are projected forward in a 16.5° beam (Au et al. 1999). Therefore, most activity will only be recorded when the porpoises are within the click detector's range and point towards the detector. A fraction of echolocation activity might be recorded after reflection from the surface or bottom. For reflected clicks, however, the sensitivity range of the click detectors (TPODs) employed here should be even lower than the estimated 170 m.

The observed combination of avoidance and exploratory behaviour shows that harbour porpoises were cautious to the new sound stimulus but showed no fear or panic, which would have led to habitat exclusion as shown in response to ADDs by Culik et al. (2001). Exploratory behaviour towards a sound stimulus could also be demonstrated by Kastelein et al. (1995) in a laboratory experiment, where a pure 2.5 kHz tone with a source level of 119 dB (re 1 µPa at 1 m) was played back to 2 harbour porpoises. The study animals investigated the sound source intensively with their biosonar, whereas a source with a 2.5 kHz sound with strong harmonics, but a slightly lower source level, induced a panic reaction.

Our theodolite data confirm the existence of this exploratory behaviour since some porpoise groups approached the active sound source by as much as 4.5 m. Visual inspection may have been the purpose of these approaches.

Harbour seals

Interpretation of the behaviour of seals in this study includes some uncertainty, since only 1 behavioural parameter was measured. However, harbour seals also showed a distinct behavioural response by increasing their median distance to the sound source when surfacing. Since only underwater sound was produced in the experiment, seals may have avoided the sound by lifting their heads out of the water, which has been reported by fish farmers using AHDs (Jefferson & Curry 1994, Creative Salmon, Tofino, pers. comm.). As opposed to this, we did not observe unusually long surface times.

Harbour seals possess better low-frequency hearing capabilities than harbour porpoises. This is necessary because male harbour seals produce communication sounds in the frequency range of 100 to 1000 Hz (Richardson et al. 1995). Møhl (1968, as cited in Terhune & Ronald 1974) reports a hearing spectrum of harbour seals between 1 and 60 kHz. Below 1 kHz, the hearing threshold increases rapidly (Kastak & Schusterman 1998). For example, at a frequency of 200 Hz a threshold of 83.8 dB (re 1 µPa) was measured, and at 75 Hz the threshold was 101.9 dB. The strongest noise from the simulated wind-turbine sound (128 dB at 160 Hz) was ca. 44 dB above the hearing threshold of a harbour seal. Using Eq. (2), this component of the noise spectrum would be reduced to the hearing threshold level at a range of 320 m. Again, correcting broadband noise to sound conditions used in controlled auditory experiments, Henriksen et al. (2001) calculated a possible hearing distance of a harbour seal to the loudest components of a small offshore wind-turbine to be 360 m, assuming cylindrical spreading. Considering that the median distance of surfacing seals shifted from 239 m in the control to 284 m when wind-turbine sound was activated, it can be assumed that seals were capable of hearing wind-turbine noise.

The occurrence of an indirect effect on seals due to prey fish avoiding the sound cannot be rejected. However, since low frequency hearing in harbour seals is better than in harbour porpoises, and porpoises obviously showed a direct response (increased periods with clicks), we assume that the main response of marine mammals is to the sound and not to the fish. Another possible explanation for the increase in distance to the sound source during sessions with wind-turbine sound is a masking effect on biologically significant sounds (such as prey sounds during foraging; cf. Southall et al. 2000).

Further aspects

Restrictions of this study

In this study it was only possible to play back wind-turbine sound emitted from a simulated 2 MW turbine with a particular spectrum recorded at a specific wind condition (8 m s^{-1}). Higher wind speeds might result in higher frequencies emitted by the faster turning gear unit, but also in higher ambient noise masking the turbine sound (Richardson et al. 1995). The results of more detailed studies may suggest that higher frequencies in the emission spectrum will lead to a more pronounced avoidance reaction, because harbour porpoises and harbour seals possess better hearing abilities at higher frequencies.

Masking

Since harbour seals produce calls in the low-frequency range (Richardson et al. 1995), these might be masked by low-frequency anthropogenic noise. Especially during the mating season, masking of males' underwater low-frequency calls by wind-turbine sound might have a negative impact on reproduction.

If low-frequency components in the clicks of harbour porpoises, as measured by Verboom & Kastelein (1995), represent communication sounds, masking of these by wind-turbine sound may be of biological significance for harbour porpoises as well. However, a masking effect might be less pronounced in harbour porpoises than in harbour seals, since their hearing range with respect to wind-turbine sound is shorter.

Habituation or desensitisation

In this context it is also relevant to know how the reaction of marine mammals to anthropogenic noise will change over time. Habituation to sound, i.e. a waning responsiveness due to a changed perception on the animal's part regarding the potential risk posed by the sound, is a phenomenon which has not been widely studied so far (cf. Richardson et al. 1995). Another aspect is desensitisation, i.e. a permanent or temporary shift in hearing sensitivity (see last paragraph, this section). In studying behaviour, it is difficult to distinguish between those two.

At least for pinnipeds some information on a fading effect is available. There has been a special focus on how to deter pinnipeds from aquaculture sites to prevent the stealing of fish. Over time, levels of acoustic harassment devices had to be increased to induce a reaction (cf. Jefferson & Curry 1994, Johnston & Woodley 1998, Taylor et al. 2001, Würsig & Gailey 2001). This shows that there is a strong potential for habituation or desensitisation, even to very aversive sounds. However, in aquaculture sites seals are 'rewarded' when ignoring the sound: Reeves et al. (1996) summarise that some seals associated prey with the sound of an AHD (dinner-bell effect).

For porpoises, Koschinski & Culik (1997) found a fading trend in the reaction to the sound of the ADD used in their experiment. Cox et al. (2001) also found some indications for this to be the case. After all, harbour porpoises and harbour seals can be observed close to major shipping routes (Hammond et al. 1995, Orthmann 2000). Ships emit high sound-energy levels at similar frequencies as offshore wind-turbines (cf. Arveson & Vendittis 2000). Since source levels played to the animals in this study were lower than those of shipping noise, it can be assumed that harbour porpoises and harbour seals can habituate to the sound of offshore wind-turbines, provided that sound spectra and intensities of future wind-turbines are similar to those simulated in this study.

The sound energy used in this study was too low to induce a temporary or permanent threshold shift. Peaks in the frequency spectrum of the wind-turbine noise were 16 dB above the hearing threshold of a harbour porpoise, and 44 dB above a harbour seal's threshold. Taylor et al. (2001) designate a received level of ca. 180 dB (re 1 µPa) as critical for porpoise hearing, which is far above the maximum source level produced in this experiment. Permanent threshold shift in pinnipeds are reported from 'seal bombs' (Würsig & Gailey 2001) and AHDs (Jefferson & Curry 1994). Kastak et al. (1999) were able to show a temporary threshold shift when the level of the sound source was 60 dB above a harbour seal's hearing threshold. In their experiment, seals tried to avoid the sound source. This may be a biologically relevant threshold for free-ranging seals and porpoises alike.

Wind farm construction and maintenance

Before and during construction of offshore wind farms, extensive noise from seismic explorations, ramming, helicopters, or increased ship traffic is to be expected (cf. Richardson et al. 1995). The effects of such sounds are potentially deleterious for marine mammals (cf. Finneran et al. 2002). For instance, during construction of the wind-turbines on sandy bottom, pile drivers are likely to be used to ram the foundations. These are capable of producing sound impulses of more than 205 dB (re 1 µPa at 1 m) (Maxon 2000).

There is not only a potential for hearing impairment, but since certain sounds will be perceivable for harbour seals and harbour porpoises at 10s or even 100s of kilometres from the construction site, such marine mammals might be excluded from critical habitat. During construction at different neighbouring or even widely spaced sites, an additive effect can be assumed. The temporary loss of habitat can strongly affect fitness if the remaining low-noise habitat is too small to maintain the population. Future studies are necessary to assess the impact and critical values of construction noise, as well as possible mitigation measures, such as:

- scheduling activities to minimise impact (e.g. avoid work during calving and reproductive periods in critical areas)
- allowing for sufficiently large low-noise habitat
- reducing sound emissions via technical measures such as bubble curtains (cf. Würsig et al. 2000).

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