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Behavioral Responses of a Harbor Porpoise (*Phocoena phocoena*) to Sounds from an Acoustic Porpoise Deterrent

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Abstract

To determine whether sounds from the FaunaGuard Porpoise Module or Acoustic Porpoise Deterrent-01 (APD-01) can deter harbor porpoises (*Phocoena phocoena*) far enough away from an offshore pile driving site to prevent hearing damage in the form of permanent hearing threshold shift (PTS) due to the first and following strikes, a harbor porpoise in a pool was exposed to the sounds at seven mean received sound pressure levels (SPLs; range: 74 to 110 dB re 1 µPa). The mean received behavioral response threshold SPL of a harbor porpoise responding to the sounds and an acoustic dose-behavioral response relationship were established. Two behavioral parameters were recorded during test and control sessions: (1) the harbor porpoise's respiration rate and (2) its distance from the transducer. Compared to in the control periods, the harbor porpoise's respiration rate increased significantly in test sessions at mean received SPLs of 104 dB re 1 µPa and above. The harbor porpoise's distance from the transducer was significantly greater during test sessions than during control sessions when mean received SPLs in test sessions were 86 dB re 1 µPa and above, indicating that it responded to the APD-01 primarily by swimming away from it. Because of the high frequency of the APD-01 sounds, harbor porpoises can determine the location of the sound source relatively easily. To calculate the effective deterring range of the APD-01 for harbor porpoises at sea, information on the behavioral threshold SPL for distance (established in the present study), the source level, and modeled information on the local propagation conditions and ambient noise need to be combined. The distance at which the APD-01 sounds are effective as deterrents is sufficient for their use to prevent PTS in wild harbor porpoises due to sound from the first strike of offshore pile driving.

Key Words: acoustics, AHD, anthropogenic noise, behavior, harbor porpoise, odontocete, conservation, offshore pile driving, disturbance, hearing, marine mammal, mitigation

Introduction

Sound is important for marine animals as a means of orientation, communication, and to locate prey, conspecifics, and predators (Richardson et al., 1995; Nowacek et al., 2007; Wright et al., 2007). Therefore, marine animals are likely to be affected by noise in their environment. In addition to natural noises, human activities increasingly create noise in the environment that may have negative behavioral or physiological effects (e.g., they may have auditory masking effects or cause temporary or permanent hearing damage) on marine fauna (National Research Council [NRC], 2003).

Coastal waters support high densities of marine fauna and are often subjected to anthropogenic sounds (e.g., from oil and gas industry operations and the construction of wind turbine parks). Although alternative methods of attaching wind generators to the sea floor are being investigated, wind turbine installation commonly involves impact pile driving with hydraulic hammers, which produces loud, impulsive sounds with ~35 to 65 strikes/min at maximum energy (as specified by the manufacturers, IHC Hydrohammer and Menck). The sound duration and level depend on the distance from the pile at which the sound is measured (generally sound duration increases and sound pressure level [SPL] decreases over distance) and the size of the pile being driven.

The effects of pile driving sounds on the harbor porpoise (*Phocoena phocoena*) are of particular interest because this species is widely distributed in the coastal waters of the Northern Hemisphere (including in locations where wind turbine parks will be built in the next decade). The harbor porpoise has acute and functional hearing over a very wide frequency range (Kastelein et al., 2010, 2015), and its hearing can be reduced temporarily (a temporary threshold shift, TTS) or permanently (a permanent threshold shift, PTS) when it is exposed to sound levels lower than those that cause such shifts in the larger odontocetes examined so far (Lucke et al., 2009; Kastelein et al., 2012a, 2013a, 2013b, 2014; Finneran, 2015). Whether TTS or PTS occurs depends not only on the received SPL, but also on the exposure duration.

The impact of pile driving sounds on the hearing of harbor porpoises can be lowered by reducing the received level. This can be done by reducing the source level (i.e., by using smaller piles), by reducing the propagation of sounds through the water (i.e., by using air curtains or bubble screens), or by increasing the distance between the animals and the sound source (i.e., by deterring porpoises from the piling location). The latter mitigation method needs to be implemented prior to the start of piling as the first few strikes can cause PTS in animals that are in the vicinity of the construction site. Later strikes may themselves deter the harbor porpoises (Carstensen et al., 2006; Tougaard et al., 2009; Brandt et al., 2011; Dähne et al., 2013; Kastelein et al., 2013c) so that the risk of PTS becomes lower once regular piling has started.

SEAMARCO designed and built the FaunaGuard Porpoise Module or Acoustic Porpoise Deterrent-01 (APD-01) to deter porpoises from piling areas before piling starts. The effective range should exceed the maximum distance at which PTS may occur in the hearing of harbor porpoises to comply with the environmental protection criteria of the national governments. The goal of the present study was to quantify the behavioral responses of a harbor porpoise in a pool to the sounds of the APD-01. Based on the dose-response relationship found in the study and the source level of the APD-01, interested parties can estimate the effective range of the APD-01 at sea, using propagation and absorption models suitable for specific piling locations.

Methods

Study Animal and Facility

The male harbor porpoise (ID No. 02) used in this study was 8 y old at the time of the study. His body weight was around 40 kg, his body length was 146 cm, and his girth at axilla was around 76 cm. His hearing was assumed to be representative of animals of his age of the same species (Kastelein et al., 2010); it was similar to that of three other young harbor porpoises tested with a psychophysical audiometric method (Kastelein et al., 2002, 2009, 2015). He received four meals of fish per day.

The study animal was kept at the SEAMARCO Research Institute, the Netherlands, in a pool complex specifically designed and built for acoustic research, consisting of an indoor pool (described in detail by Kastelein et al., 2010) and an outdoor pool (12 × 8 m, 2 m deep) in which this study was conducted (Figure 1). The walls of the outdoor pool were made of plywood covered with polyester and 3-cm-thick coconut mats with their fibers embedded in 4-mm-thick rubber (reducing reflections mainly above 25 kHz). The bottom was covered with sand. The water circulation system and the aeration system for the bio-filter were made to be as quiet as possible and were switched off before sessions and kept off during sessions so that there was no current in the pool. The APD-01 used to produce the sound stimuli was housed in a research cabin next to the pool out of sight of the study animal (Figure 1; see also Kastelein et al., 2012b).

Audio and Video Equipment

The sounds were produced by the APD-01 with the modification that the output could be controlled with two custom-built digital attenuators (Figure 2). The attenuation system was linear over the entire SPL range used in the study. The transducer was placed at the southwestern end of the outdoor pool at 2 m depth (Figure 1).

In common with the audible ambient noise (see next section), the APD-01 sounds were monitored via a custom-built hydrophone (100 Hz to 150 kHz) and a custom-built conditioned charge pre-amplifier. The output of the pre-amplifier was digitized via the analog-to-digital converter (König – USB 2.0 audio/video grabber) and recorded on the computer in synchrony with the video images. The output of the pre-amplifier was also fed to an amplified loudspeaker (Medion – MD5432) so that the operator in the research cabin could monitor the ambient noise during sessions. The APD-01 contains an ultrasound listening device that is connected to a hydrophone (100 Hz to 150 kHz), enabling the operator to hear the converted ultrasound (frequency divided by 10 to make it audible) produced by the APD-01.

The sound field produced by the APD-01 and the ambient sound in the pool were measured while the animal was not present in the pool. The recording and analysis equipment consisted of two B&K 8106 hydrophones (10 Hz to 140 kHz), a B&K PULSE 3560 D multichannel high-frequency analyzer, and a laptop computer with B&K PULSE software, *Labshop*, Version 12.1. The system was calibrated with a B&K 4223 pistonphone. The recordings were made with a 22.4 Hz high-pass filter and at a sample rate of 524,288 Hz.

The animal's behavior was filmed from above by a waterproof camera (Conrad – 750940) with a

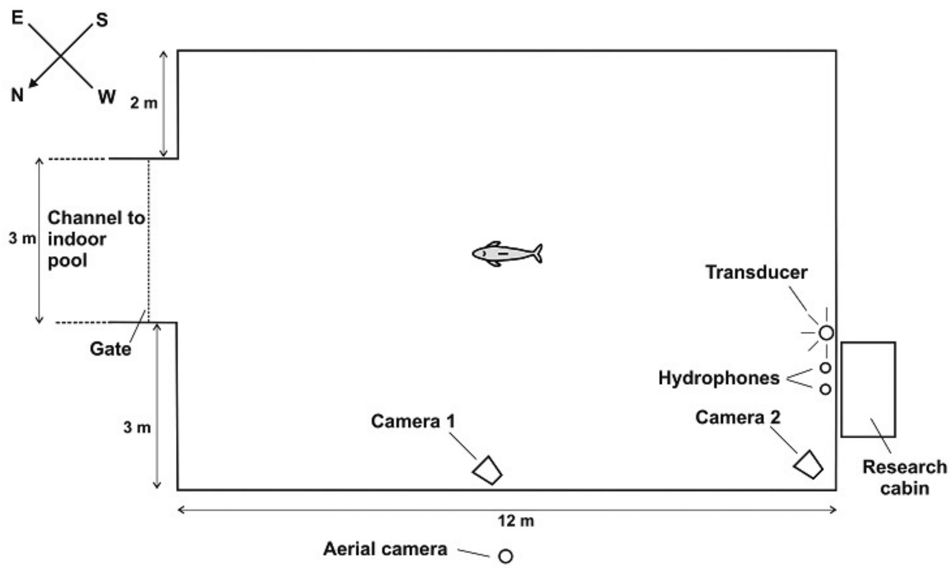

Figure 1. Top-scale view of the study facility, showing the study animal, the location of the aerial camera, the two cameras just above the water surface at the edge of the outdoor pool, the underwater transducer emitting the sounds, and the hydrophones (used to listen to the FaunaGuard Porpoise Module or Acoustic Porpoise Deterrent [APD-01] sounds and ambient noise). Also shown is the research cabin that housed the audio and video equipment and the operator.

wide-angle lens and a polarizing filter to prevent saturation of the video image by glare from the water surface. The camera was placed on a pole 9 m above the water surface on the northwestern side of the pool (Figure 1). The entire surface of the pool was captured on the video image. The output of the camera was fed through a video multiplexer (MX-8 – CSX) that added the time and date to the images. Thereafter, the output was digitized by an analog-to-digital converter (König – grabber) and stored on a laptop computer (ACER Aspire 5750G). The animal was also filmed by two black-and-white video cameras (Ocean Systems Inc. – Delta Vision) on the northwestern side of the pool, just above the water surface (Figure 1). The images from these cameras were not recorded and were visible to the operator in the research cabin on two monitors (MT Logic). These cameras allowed the operator to count the harbor porpoise's respirations accurately.

Character of Test Stimuli

The output of the transducer producing the APD-01 sounds was recorded in the pool (hydrophone 1 m from the source; both hydrophone and transducer at a depth of 1 m). The APD-01 produces eight sounds (varying in duration between 9 and 18 s) at random intervals, varying between 3 and 10 s. The average duty cycle of the APD-01 sounds is 65%. The sounds cover a frequency range between approximately 60 and 150 kHz (Table 1 & Figure 3). There are no silent intervals within the eight sounds.

SPL Characterization of APD-01 Sounds

The sounds were characterized in terms of their SPL (in dB re 1 μPa), determined over the duration (t_{90} in s) of an individual signal in the sound. The duration was determined as the time interval between the points when the cumulative sound exposure (the integrated broadband sound pressure squared) reached 5 and 95% of the total exposure (i.e., the duration contained 90% of the total energy in the signal; Madsen, 2005). All signals were high-pass filtered (cut-off frequency 100 Hz) and low-pass filtered (cut-off frequency 150 kHz) with a 3rd order Butterworth filter.

SPL Distribution During Emission of APD-01 Sounds

To determine the sound distribution in the pool, the SPL of the APD-01 sounds was measured at 77 locations at three depths (0.5, 1.0, and 1.5 m) using a consistent source level of 145 dB re 1 μPa for these measurements. The reported SPLs were from one signal per sound per location; and except for Sound 7, all sounds had very similar spectra (Figure 4). The measured distribution of the received SPLs at the 231 positions in the pool is shown in Figure 5; the mean (over all of the

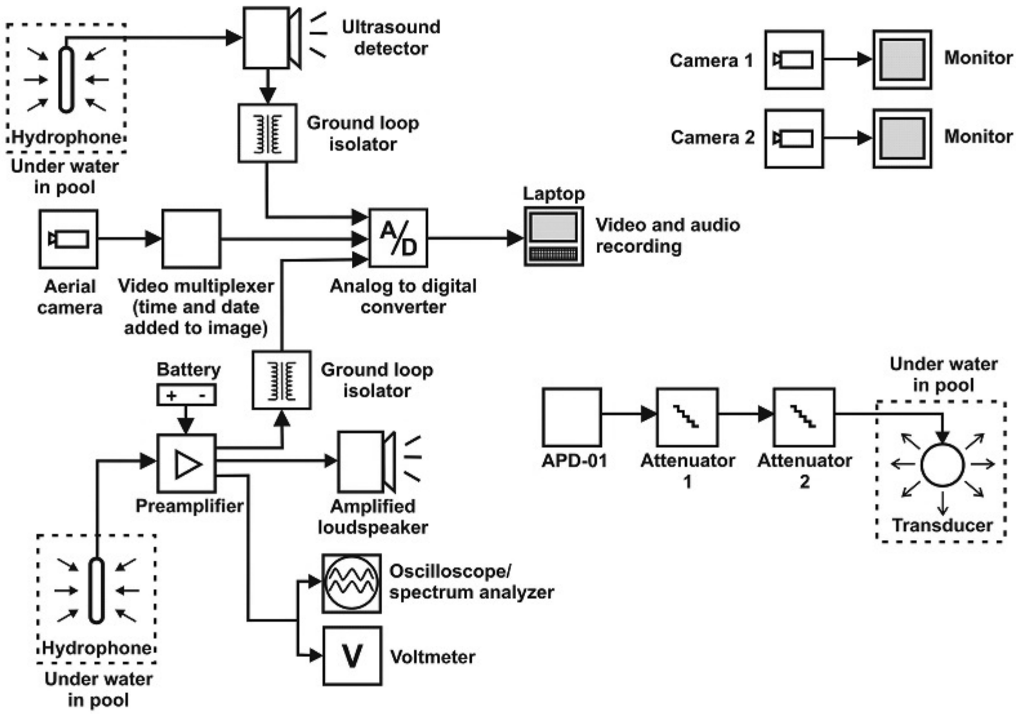

Figure 2. Block diagram of the equipment used to produce and modify sounds, and to visualize and record the behavioral responses of the harbor porpoise (*Phocoena phocoena*)

Table 1. The eight sounds produced by the FaunaGuard Porpoise Module (also called Acoustic Porpoise Deterrent-01 or APD-01); there are no silent intervals within the eight sounds. CW = continuous wave.

Sound	Description of sound
1	Sweep: 60-150 kHz; step: 1 kHz; step duration: 5 ms; repeated 20 times
2	Sweep: 60-150 kHz; step: 5 kHz; step duration: 30 ms; repeated 20 times
3	Sweep 60-70 kHz; step: 1 kHz; step duration is 5 ms
	Sweep 60-85 kHz; step: 1 kHz; step duration is 5 ms
	Sweep 70-100 kHz; step: 1 kHz; step duration is 5 ms
	Sweep 85-115 kHz; step: 1 kHz; step duration is 5 ms
	Sweep 90-150 kHz; step: 1 kHz; step duration is 5 ms
	The group of sweeps above is repeated 15 times.
4	Sweep 60-80 kHz; step: 1 kHz; step duration is 25 ms
	Sweep 60-120 kHz; step: 1 kHz; step duration is 15 ms
	Sweep 60-150 kHz; step: 1 kHz; step duration is 5 ms
	The group of sweeps above is repeated 10 times.
5	Sweep 60-150 kHz; step: 1 kHz; step duration is 10 ms; repeated 15 times
6	Sweep 60-100 kHz; step: 1 kHz; step duration is 25 ms
	Sweep 100-60 kHz; step: 1 kHz; step duration is 25 ms
	The group of sweeps above is repeated five times.
7	80 kHz CW, duration 200 ms, then silence, duration 100 ms; repeated 30 times
8	Sweep 60-100 kHz; step: 1 kHz; step duration is 10 ms
	Sweep 100-60 kHz: step: 1 kHz; step duration is 10 ms
	The group of sweeps above is repeated 20 times.

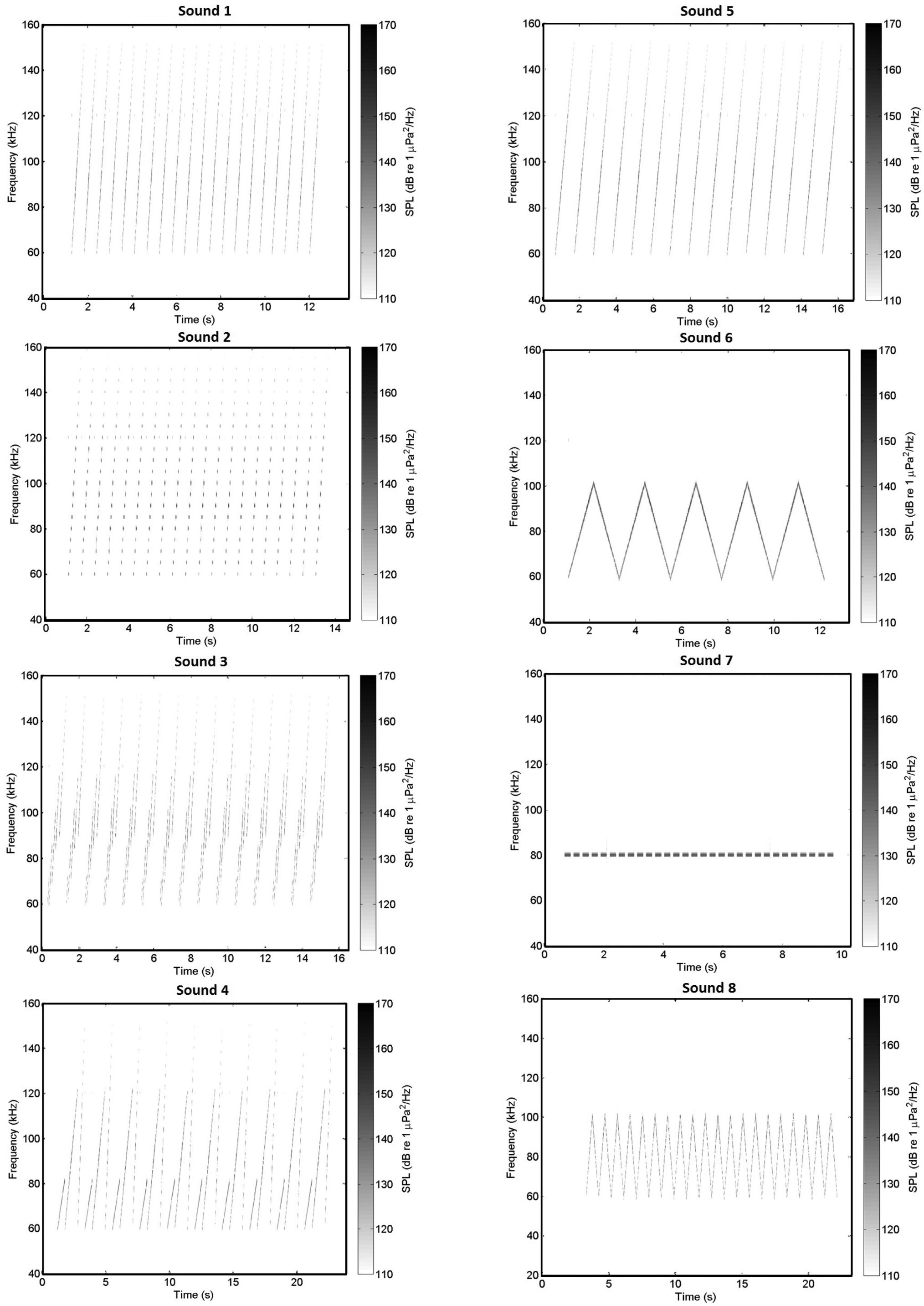

Figure 3. Sonograms of the eight sounds produced by the FaunaGuard Porpoise Module (APD-01) in the pool, measured at a distance of 1 m from the source and at a depth of 1 m. Broadband source level during the recordings (maximum level that can be produced by the APD-01): 172 dB re 1 µPa. Because the dynamic range is kept the same (60 dB) in all figures, parts of some signals are lighter grey (indicating a low SPL).

231 measurement locations) received broadband SPL (mean over all eight sounds) for this specific recording was 140 dB re 1 µPa per depth. Levels decreased with increasing distance from the transducer.

Sound Pressure Levels of the APD-01 Sounds and Ambient Noise

During a pilot study, the mean received SPL of the APD-01 sounds was gradually (within 2 min) increased to a level just below that at which the harbor porpoise's swimming and respiration behavior changed, and he swam slightly away from the sound source. This level (74 dB re 1 µPa) was selected as the lowest level to be used in the experiment. Seven levels in steps of 6 dB were tested to show the dose-response relationship; the difference between the lowest and highest exposure SPLs was 36 dB. Even at the maximum test SPL, the well-being of the harbor porpoise did not seem to be severely compromised (his swimming speed and respiration rate were similar to that during rainfall), but he swam more often at the opposite side of the pool from the APD-01 transducer. During the tests, the sound sequences were produced at seven source levels within this 36 dB range (6 dB steps), resulting in mean received SPLs of 74, 80, 86, 92, 98, 104, and 110 dB re 1 µPa (offered in random order to the harbor porpoise). The sounds were emitted at varying intervals of 3 to 10 s (with an average duty cycle of 65%). Therefore, the equivalent SPLs (Leq) of the APD-01 sounds were, on average, 2 dB lower than the SPLs indicated in this paper (10*log10(0.65)).

The normal ambient noise level in the pool was low (Figure 6). Above 3.5 kHz, the measured ambient noise level was mainly determined by the self-noise of the recording equipment.

Experimental Procedure

The transducer producing the APD-01 sound sequences was positioned in the water at the southwestern end of the pool at the start of each day (Figure 1). Tests consisted either of 30-min test sessions (sound sequence emission, $n = 12$ per SPL, average duty cycle: 65%) or 30-min control sessions (no sound emission, $n = 12 \times 7 = 84$). The order of these two session types was random. The seven mean received SPLs were also tested in random order during the study period. Two to four sessions were conducted per day (50% test and 50% control), 5 d/wk, beginning between 0800

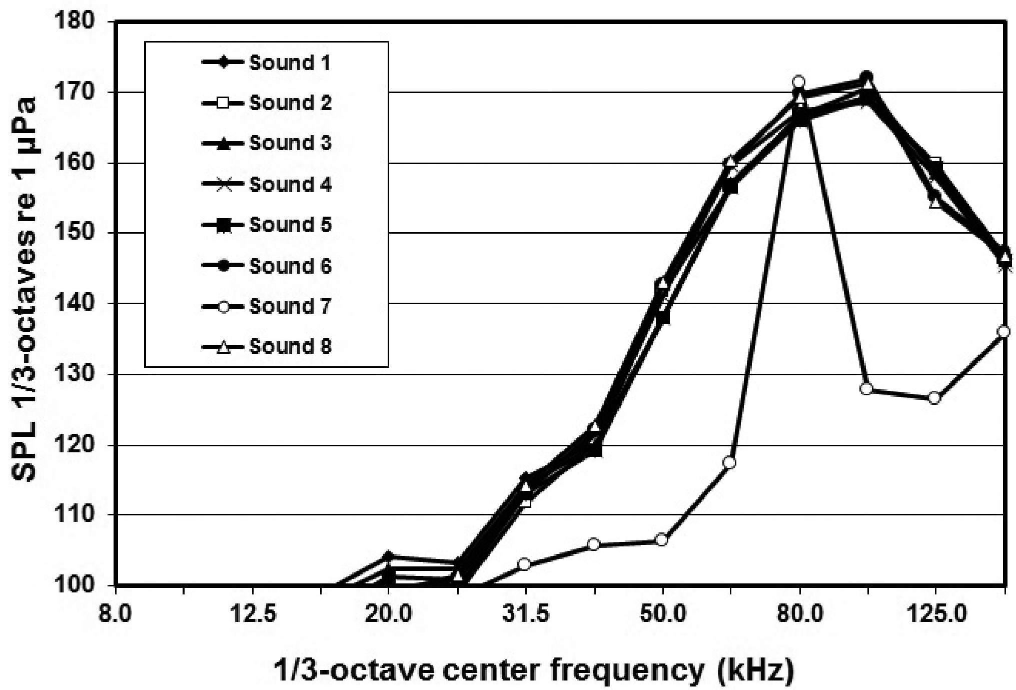

Figure 4. The ⅓-octave spectra of the eight sounds of the APD-01 recorded at 1 m from the transducer at 1 m depth at the maximum broadband source level of the APD-01 (172 dB re 1 µPa); all spectra of the broadband sounds are similar, with the exception of the spectrum of Sound 7 which is tonal.

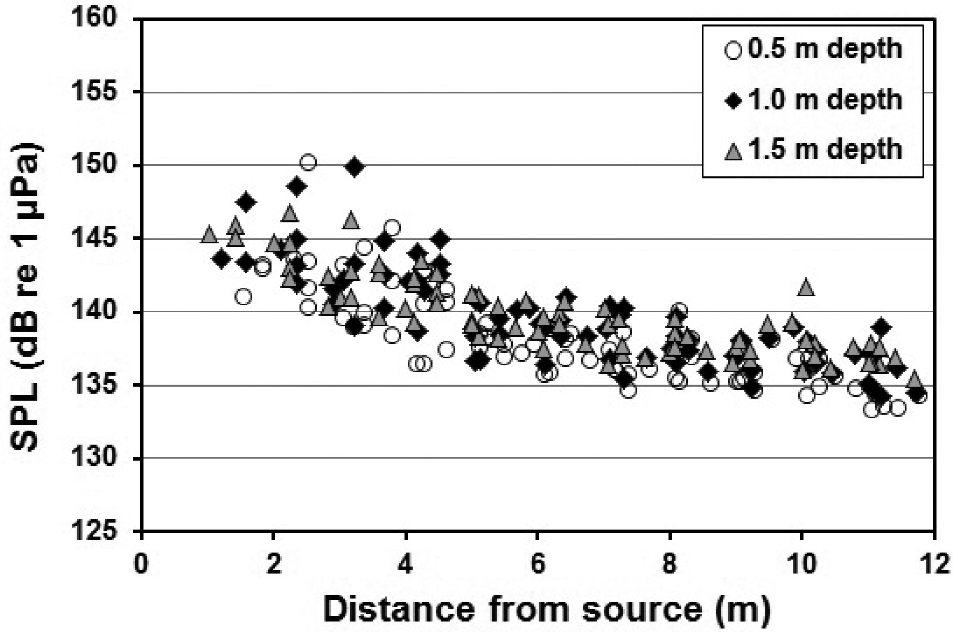

Figure 5. The SPL distribution of the APD-01 sounds in the pool, as a function of the distance from the transducer, for three depths (0.5 m: ○, 1.0 m: ◆, and 1.5 m: Δ; $n = 77$ measurements/depth). Broadband source level in this case was 145 dB re 1 μPa. Mean received broadband SPL for this particular recording was 140 dB re 1 μPa.

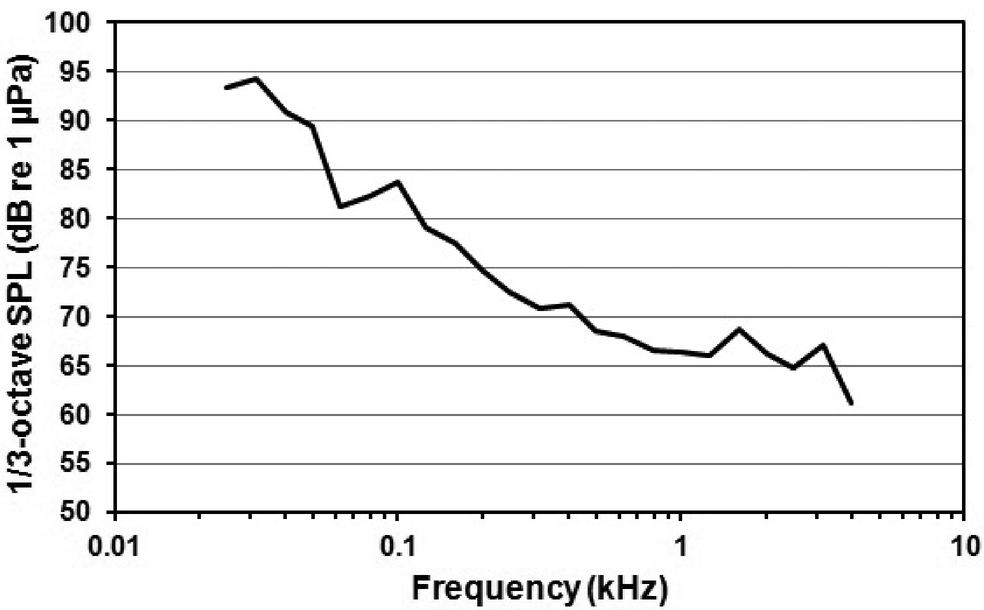

Figure 6. The mean SPL (of measurements at three depths) of ambient noise in the pool represented in 1/3-octave bands (SPL averaged over 10 s). The level is very low—for most of the spectrum, it is below the level measured during Beaufort sea state 1 at sea. Above 3.5 kHz, the noise level was determined by the self-noise of the recording system.

and 1530 h. During the sessions, only the operator was allowed within 10 m of the pool; she sat very still inside the cabin and was not visible to the harbor porpoise.

To prevent masking of the sounds by ambient noise, tests were not carried out during rainfall or when wind speeds were above Beaufort sea state 4. The study was conducted between February and May 2014.

Response Parameters and Behavioral Data Recording

Two objective behavioral parameters were used to quantify the harbor porpoise's responses to the sounds: (1) his number of respirations in each session and (2) his mean distance from the transducer (based on the mean distance of all his surfacing locations in the pool from the transducer). These parameters were quantified and compared for test and control sessions.

The study animal's distance from the transducer was quantified as follows to determine whether he responded to the sounds by swimming away from the sound source: from video camera recordings, the locations where the harbor porpoise surfaced during the test and control sessions were recorded on a grid superimposed on the computer screen. The grid corresponded to a pool grid of 1 × 1 m and was made by connecting lines between 1-m markers on the pool's sides. The grid square in which the harbor porpoise surfaced was determined, and the center point of the grid square was used to calculate the distance between his surfacing location and the transducer via triangulation (ignoring depth at which he was swimming between surfacings). The water was always clear; and when light conditions (which depended on the weather and the time of day) were such that the bottom of the pool was visible, the harbor porpoise could be seen well below the water surface. He did not swim far away from the surfacing locations, so the surfacing locations were a good indication of his general swimming area.

Analysis

To investigate the harbor porpoise's response to the APD-01 sounds in control sessions and at the seven levels presented in test sessions, a one-way ANOVA was carried out for each of the two response variables (number of respirations and distance from the transducer). Bonferroni simultaneous post-hoc tests were used to compare the levels in each test session with those in the control sessions. For all analyses, assumptions of the tests were conformed to, and the level of significance was 5% (Zar, 1999). Analysis was conducted in *Minitab*, Version 13 (www.minitab.com).

Results

During control sessions, the harbor porpoise usually swam large clock-wise ovals in the pool. The animal's mean number of respirations (118 ± 5.4 breaths in 30 min - mean ± standard deviation; Figure 7a) and the mean distance between his surfacing locations and the transducer (4.8 ± 1.1 m; Figure 7b) were similar in all 12 control sessions. The animal never jumped during the control sessions.

During test sessions with APD-01 sounds with low SPLs, the harbor porpoise's behavior was similar to his behavior during control sessions (Figure 7); but at higher SPLs, he responded to the sounds by swimming away from the transducer, increasing his respiration rate, and jumping out of the water. Comparison of the behavioral parameters (number of respirations and distance from the transducer) in the test and control sessions by means of ANOVAs (Table 2) showed that both response variables were significantly affected by the mean SPL of the sounds. Post-hoc tests showed that the number of respirations was significantly higher in test sessions than in control sessions only when the mean received sound level was 104 dB re 1 µPa or higher (Figure 7a). Significant movement away from the transducer occurred at mean SPLs of 86 dB re 1 µPa and higher (Figure 7b). The values indicated in Figure 7 (104 and 86 dB re 1 µPa), therefore, are considered to be the SPL thresholds for behavioral response. The behavioral thresholds expressed as equivalent SPLs are 0.1 dB lower than those indicated above. The harbor porpoise responded to the APD-01 primarily by swimming away from it, but also, to a lesser extent, by increasing his respiration rate. He occasionally jumped out of the water during the test sessions (mean ≤ one jump per session).

Discussion

The harbor porpoise in the present study responded to the APD-01 sounds. His behavioral response threshold SPL for moving away from the transducer was lower than that for increasing his respiration rate. The sound gradient in the pool was much steeper than in previous studies in which sounds with lower frequencies were used (Kastelein et al., 2013b, 2014), so by swimming away from the transducer, the harbor porpoise could lower its received level. Perhaps he then became calmer, which was reflected in the more limited increase in his respiration rate.

After each session, the animal's behavior immediately returned to normal; being exposed to the APD-01 sounds at the levels used in this study for

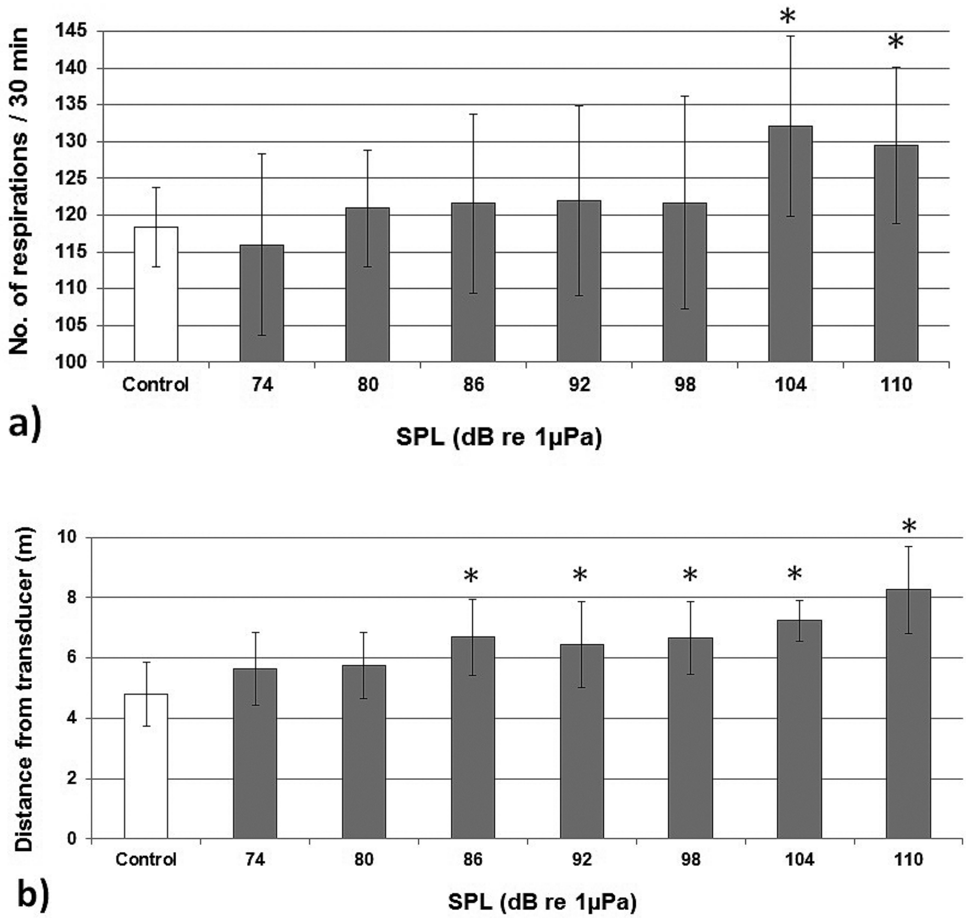

Figure 7. The mean number of respirations by the harbor porpoise (a) and his mean distance from the transducer (b) during 30-min test sessions and 30-min control sessions, showing his response to the seven mean received SPLs of the APD-01 sounds (*n* =12 for each SPL). Each bar indicates two standard deviations (SDs), and * indicates a test session value that differed significantly from the control session value (Bonferroni simultaneous post-hoc tests). The harbor porpoise responded to the APD-01 primarily by swimming away from it, but also, to a lesser extent, by increasing its respiration rate.

Table 2. Results of one-way ANOVAs for the response variables "number of respirations" and "distance from the transducer," showing the harbor porpoise's (*Phocoena phocoena*) response to sounds of different levels produced by the APD-01. df = degrees of freedom, MS = mean square, F = test statistic, and *p* = probability.

Number of respirations (in 30-min sessions)				
Source of variation	df	Adjusted MS	F	*p*
Level	7	349.0	2.71	0.014
Error	88	128.8		
Total	95			
Distance from the transducer (mean)				
Source of variation	df	Adjusted MS	F	*p*
Level	7	13.406	9.42	0.000
Error	88	1.423		
Total	95			

30 min had no lasting effect on the animal's behavior. A quick return to normal behavior had been seen in previous acoustic alarm (pinger) and pile driving sound playback studies with harbor porpoises (Kastelein et al., 2000, 2001, 2006, 2008a, 2008b, 2013c) and was the reason for not including a posttest observation period as was done in a previous pinger study (Kastelein et al., 2000).

The response of the study animal to the APD-01 sounds may not have been representative for its species. Behavioral response studies should be conducted with as many animals as possible as responses to acoustic stimuli vary between individual harbor porpoises (Kastelein et al., 2000, 2001, 2008b). Behavioral responses to sounds are also context-dependent, depending on the occurrence of attractive and aversive components in the environment. The specific conditions of the pool do not occur in the wild, though situational contexts in the wild are innumerable. However, it is unlikely to be possible, in the near future, to conduct a similar experiment with another harbor porpoise as the number of captive harbor porpoises is small, and most facilities are not designed for this type of behavioral response study. Therefore, the results of this study are rare and valuable. The next step should be to conduct a similar study in the wild in conditions where harbor porpoises can be observed in the vicinity of the underwater transducer of the APD-01.

Due to habituation, an effective acoustic deterrent sound that provokes aversive behavior under laboratory test conditions may not produce aversive behavior after frequent repetitions in nature. In the present study, no attempt was made to estimate habituation effects. However, the APD-01 is intended to be used only locally and during relatively short periods of time (h) in contrast to deterrent devices used on gillnets to prevent fisheries bycatch that are used on a large scale and for days in a row. Whether individual harbor porpoises will hear the APD-01 sounds more than once and, thus, have a chance to habituate to them depends on the number of APD-01s that are deployed, the duration that they are deployed, and on the geographical movements of harbor porpoises at sea. More information about local populations and individual movements of harbor porpoises would be helpful in determining whether or not they are likely to encounter the APD-01 sounds more than once. Such information would add to the value of studies like the present one.

The hearing sensitivity of a harbor porpoise for a sound depends on the direction from which the sound comes relative to the body axis of the animal. The received directionality of sound also depends on the frequency content of the signal: an increase in frequency results in an increase in the directivity index (Kastelein et al., 2005). The broadband signals used in the APD-01 have most of their energy between 60 and 150 kHz, so the effect of directivity was substantial (~12 dB), and the perceived level was dependent on the position of the harbor porpoise relative to the sound source. The high frequency of the signals used in the APD-01 make it easy for a harbor porpoise to determine the location of the sound source (by changing its position relative to the sound source so that the perceived level changes; Kastelein et al., 2007) and to swim away from it as intended.

The APD-01 was designed to deter harbor porpoises, and the threshold SPL for the distance from the transducer can be used to calculate the effective distance of the APD-01 sounds at sea. To calculate the deterring distance or effective range of the APD-01 for harbor porpoises at sea, information on the source level, the behavioral threshold level for distance (~86 dB re 1 μPa SPL, as established in the present study), and modeled information on the local propagation conditions and ambient noise need to be combined. For the Luchterduinen Wind Turbine Park project (the construction of a wind farm near the Dutch coast), the best available data were used to estimate the maximum distance from the piling site at which PTS could occur in harbor porpoises (Technisch Natuurwetenschappelijk Onderzoek [TNO] memo TNO-060-DHW-2013-02724). It was estimated that PTS could occur within 500 m of the piling site, or within 1,000 m if the influence of wind noise was not taken into account. The regulatory agency of the Netherlands government uses the prevention of PTS as the environmental impact criterion, so to avoid an adverse impact on hearing, any deterring device should deter harbor porpoises at least up to a distance of 500 m in average wind conditions in the period in which construction is allowed (July-December), and up to around 1,000 m in low wind conditions. Based on the result from the present study, for a specific construction site in the North Sea, the Luchterduinen Wind Turbine Park, TNO has calculated the effective distance of the APD-01 to be ~1.3 km (without the influence of background noise; de Jong & Binnerts, 2014). The distance at which the APD-01 becomes effective as a deterrent is sufficient to warrant its use to prevent PTS in harbor porpoises due to pile driving sounds. However, the effective range may be reduced if the sounds of the APD-01 are masked by background noise. This effect was seen for 6 to 7 kHz sonar sweeps (Kastelein et al., 2011). To what extent the very high-frequency signals of the APD-01 will be masked by background noise is not yet clear.

Conclusions

The harbor porpoise in the present study responded to the APD-01 sounds by swimming away from the sound source, and his response increased as the sounds became louder. Assuming that most harbor porpoises respond in the same way, the APD-01 is likely to be successful when deployed at sea to deter harbor porpoises from pile driving sites. Its success is due in large part to the directional nature of the high-frequency sounds it produces. To calculate the deterring distance or effective range of the APD-01 for harbor porpoises at sea, information on the source level, the behavioral threshold level for distance (~86 dB re 1 μPa SPL as established in the present study), and modeled information on the local propagation conditions and ambient noise need to be combined. For a specific construction site in the North Sea (Luchterduinen Wind Turbine Park), the effective distance is estimated to be sufficient to warrant the use of the APD-01 to prevent PTS in harbor porpoises.

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