Aquatic Mammals 2022, *48*(2), 97-109, DOI 10.1578/AM.48.2.2022.97

Behavioral Responses of a Harbor Porpoise (*Phocoena phocoena*) Depend on the Frequency Content of Pile-Driving Sounds

Ronald A. Kastelein,[1] Christ A. F. de Jong,[2] Jakob Tougaard,[3]
Lean Helder-Hoek,[1] and Linde N. Defillet[1]

[1]*Sea Mammal Research Company (SEAMARCO), Julianalaan 46, 3843 CC Harderwijk, the Netherlands*
E-mail: rk@seamarco.nl
[2]*TNO Acoustics and Sonar, Oude Waalsdorperweg 63, 2597 AK, The Hague, the Netherlands*
[3]*Aarhus University, Department of Bioscience, C. F. Møllers Allé 3, Building 1131, 8000 Aarhus, Denmark*

Abstract

The loud, impulsive, broadband underwater sounds produced during offshore pile driving are known to have auditory and behavioral effects on harbor porpoises (*Phocoena phocoena*) in the areas around piling sites. Thresholds to prevent behavioral effects have not yet been set, and it is unclear whether or not auditory frequency weighting of piling sounds, as used for criteria to protect hearing (Southall et al., 2019), is also useful for predicting behavioral responses and therefore required to set safety criteria and develop mitigation measures. A harbor porpoise in a pool was exposed to playbacks of piling sounds, and her behavioral responses were quantified in comparison to baseline periods without piling sounds. The full-spectrum playback piling sound was recorded at 100 m from a piling site for an offshore wind turbine. For comparison, five low-pass filtered (6.3, 3.2, 1.5, 1.0, and 0.5 kHz) versions of the sound in which the bandwidth decreased were played back at the same duty cycle (46 strikes/min) and similar single-strike sound exposure levels (power average in the pool: 135 dB re 1 µPa^{2}s; t_{90}: 90 to 100 ms). As the bandwidth of the piling sounds decreased, the porpoise's behavioral response became weaker. Although these results are based on only one porpoise, they indicate that harbor porpoises respond most strongly to the higher frequencies in piling sounds. Therefore, frequency weighting of the sound exposure level (SEL) will improve prediction of behavioral responses, and behavioral response threshold levels for criteria should also be expressed as weighted SELs. However, it is unclear whether the weighting for predicting auditory effects is also the best weighting to predict behavioral effects. Mitigation of the effects of piling sounds on harbor porpoise behavior should be focused on reducing the high-frequency part of the spectrum.

Key Words: acoustics, auditory frequency weighting, behavior, coastal waters, conservation, disturbance, habitat, mammals, marine ecology, noise, odontocete, mitigation, offshore, offshore wind farms, wind energy

Introduction

Sound is important for odontocetes (toothed whales) as a means of orientation and communication, and to locate prey, conspecifics, and predators (Richardson et al., 1995; Nowacek et al., 2007; Wright et al., 2007). Therefore, odontocetes are likely to be disturbed by extraneous noise in their environment. In addition to natural sounds, human activities increasingly add noise to the environment, which may have negative effects on odontocetes by causing auditory masking, temporary or permanent hearing threshold shifts, or behavioral effects (National Research Council [NRC], 2005).

Coastal waters support high densities of odontocetes and are heavily used by humans producing noise through, for example, shipping, construction of harbors, oil and gas industry operations, and construction of offshore wind farms. Although alternative methods of attaching wind turbines to the sea floor are being investigated, installation commonly involves percussion pile drivers, which produce high-amplitude, impulsive sounds.

The effects of pile-driving sounds are of particular interest in relation to the harbor porpoise (*Phocoena phocoena*) because it has a wide distribution area in the coastal waters of the Northern Hemisphere, acute hearing, and functional hearing over a wide frequency range (Kastelein et al., 2017). Piling sound can reduce the ability of harbor porpoises to catch fish (Kastelein et al., 2019b) and can cause them to flee from areas around piling sites (Tougaard et al., 2009; Dähne et al., 2013). Kastelein et al. (2013c) conducted a dose-response study by exposing a harbor porpoise in a pool to recordings of pile-driving sounds made 100 m from a piling site. At frequencies above 0.63 kHz, the spectrum recorded at sea could be mimicked in the pool. Calculations based on a broadband sound exposure level (SEL) threshold suggested that harbor porpoises avoid piling noise up to a distance of 30 km away from a piling site (Kastelein et al., 2013c). This distance is at the high end of distances over which harbor porpoises have been observed to avoid piling sounds (Tougaard et al., 2009; Bailey et al., 2010; Brandt et al., 2011, 2018; Dähne et al., 2013; Haelters et al., 2014; Graham et al., 2019).

The received spectrum, received level, and received duration of pile-driving sounds depend on properties of the pile (e.g., diameter, length, shape, wall thickness, depth in the sediment, etc.), the hammer size, the use of noise abatement methods, the environment (e.g., substrate, water depth, etc.), the propagation conditions, and the distance from the sound source at which the sound is measured (Bellmann et al., 2020; Martin et al., 2020). At sea, as the distance from a piling sound source increases, the energy in the high-frequency part of the piling sound's spectrum is reduced. This is because water acts as a low-pass filter by reducing sound with wavelengths that are larger than the water depth (Ainslie, 2010). Noise abatement measures such as air bubble screens also are more effective in reducing the high-frequency noise components. Hearing sensitivity in harbor porpoises increases sharply between 0.1 and 20 kHz (Kastelein et al., 2017) such that, depending on the level, the high-frequency part of a sound's spectrum may determine both the audibility of the sound (Kastelein et al., 2011) and the severity of the behavioral response to it (Kastelein et al., 2012, 2013a, 2014, 2015b, 2019a; Dyndo et al., 2015).

At present, unweighted received sound levels are used to assess the impact of pile-driving sound on harbor porpoise behavior. The aim in the present study was to compare the response of a harbor porpoise to playbacks of piling sounds at a duty cycle commonly used when driving monopiles for offshore wind turbines, with six different spectra due to differing degrees of low-pass filtering. The filtering was used to eliminate, to differing degrees, the higher frequency components for which the porpoise hearing is more sensitive, while the acoustic energy in the piling sounds was kept constant (all six sounds had the same broadband unweighted SEL). The ultimate goal was to improve predictions of behavioral responses of harbor porpoises to pile-driving sounds. As suggested by Tougaard et al. (2015), frequency weighting with a function approximating the inversed porpoise audiogram might be appropriate when assessing impact of impulsive (piling) sounds. We address the following question: Is behavioral response in the harbor porpoise better explained by frequency-weighted metrics as used for assessing hearing threshold shifts (Southall et al., 2019) or by unweighted metrics?

Methods

Study Animal and Facility

The female harbor porpoise (F05) used in this study was 9 to 10 years old, her body weight was ~44 kg, her body length was 155 cm, and her girth at axilla was ~ 80 cm. Her hearing was assumed to be representative, as it was similar to that of four other harbor porpoises (Kastelein et al., 2017). She 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 the present study was conducted (Figure 1). The walls of the outdoor pool were made of plywood covered with nets on which aquatic vegetation grew (reducing high-frequency reflections). The bottom was covered with sloping sand. The water circulation system and the aeration system for the biofilter were made to be as quiet as possible (< Sea State 1), and the pumps were switched off during the entire day when the sessions were conducted so that there was no current in the outdoor pool. The equipment used to generate the sound stimuli was housed out of sight of the study animal in a research cabin next to the pool (Figure 1).

Acoustics

Background Noise—The background noise in the outdoor pool was measured twice during the study, between 0.025 and 160 kHz, under conditions that were typical for the sessions (i.e., circulation pumps switched off, no rain, and wind force Beaufort ≤ 4). The background noise level was low (Figure 2). Above 3.2 kHz, the recorded level was so low that it was mainly determined by the self-noise of the recording equipment.

Test Stimuli—The effect of the frequency content of sounds on the study animal's behavioral response was tested by playing back filtered pile-driving sounds. Offshore pile-driving sounds were recorded at 100 m from a foundation pile that was being driven into the seabed for a wind turbine in the Dutch offshore wind farm "Egmond aan Zee." A WAV file was made of a series of five consecutive pile-driving strike sounds with a strike rate of 46 strikes per minute. The recording was sampled

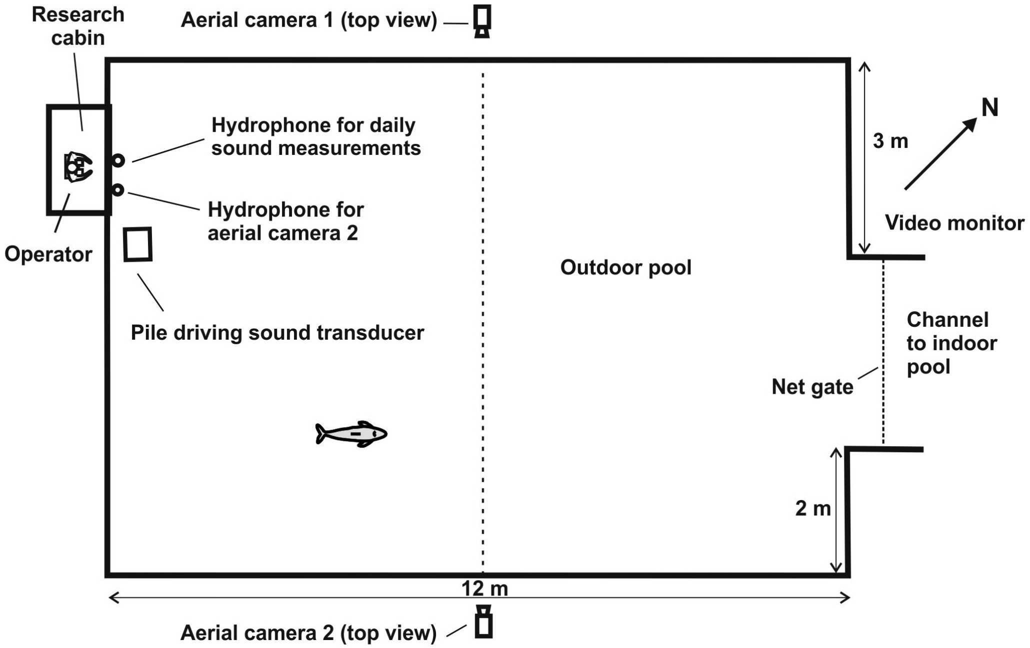

Figure 1. Top scale view of the outdoor study facility, showing the female harbor porpoise (*Phocoena phocoena*) and the locations of aerial camera 1 (8 m above the water level), aerial camera 2 (5 m above the water level), the underwater transducer emitting the piling sounds at the bottom of the pool, the hydrophone (used to listen to the piling sounds and background noise), and the research cabin, which housed the video and audio equipment, and the operator/data collector. The pool was 2 m deep. The central dashed line shows the division of the pool into two halves (see Tables 1 & 2).

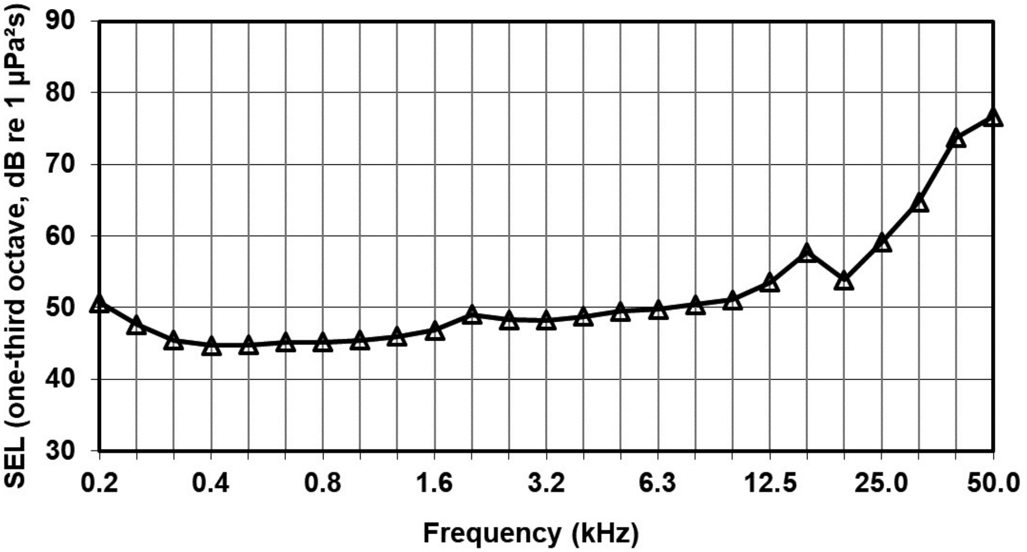

Figure 2. The mean background noise in the outdoor pool, represented in one-third-octave (base-10) bands. Each mean was calculated from measurements at three depths, and the sound pressure level was averaged over 10 s and converted to sound exposure level (SEL) for a 100 ms time period by adding $10\log_{10}(0.1)$. The level is very low; for most of the spectrum, it is below the level measured at Sea State 1 in the open sea. Above 3.2 kHz, the background noise level is dominated by the self-noise of the recording system.

at 88.2 kHz sample frequency and high-pass filtered (2nd order Butterworth) at 0.5 kHz because lower frequencies could not be reproduced efficiently due to the characteristics of the transducer and, to some extent, due to the limited water depth in the pool (2 m; Kastelein et al., 2013a). This playback sound, which has been used in previous pool studies (Kastelein et al., 2013b, 2013c), is referred to as sound 1, or the "full-spectrum" playback piling sound.

The full-spectrum playback piling sound was further modified by means of low-pass filtering (2nd order Butterworth). Five filter frequencies were selected, at center frequencies of one-third-octave (base-10) bands between 0.5 and 20 kHz. The amplitude of the five reduced-spectrum piling sounds was adjusted to keep the unweighted broadband SEL as consistent as possible for all six piling sounds (Table 1), and the six piling sounds were played back at the same duty cycle. Single-pulse SEL was selected as the appropriate metric to describe the magnitude of exposure, and to maintain consistency with previous studies and with legislation in some countries bordering the geographic range of the harbor porpoise, such as Germany.

Playback Equipment—The digitized sequences (WAV files; sample frequency 88.2 kHz, 16-bit) were played back in a loop by a laptop computer (Model 5750G; Acer Aspire, Taipei, Taiwan) with a program written in *LabVIEW* to an external data acquisition card (Model USB6259; National Instruments [NI], Austin, TX, USA); the output was digitally controlled in 1 dB steps with the *LabVIEW* program. The output of the data acquisition card went through a custom-built buffer to a power amplifier (Model LS5002; East & West, Seoul, South Korea) which drove the transducer (Model LL1424HP; Lubell, Columbus, OH, USA) through an isolation transformer (Model AC1424HP; Lubell). The transducer was placed on the pool floor, parallel to the bottom, at the southwestern end of the outdoor pool (Figure 1).

Before each session, a 1.5 kHz FM signal was used to monitor the output of the sound system to the transducer via an oscilloscope (Model 2201; Tektronix, Beaverton, OR, USA) and a voltmeter (Model GDM-8255A; GW Instek, New Taipei City, Taiwan). The underwater sound was monitored with a custom-built hydrophone connected via a spectrum analyzer (Model PCSU1000; Velleman, Gavere, Belgium) to a laptop computer (Model NP-N145; Samsung, Suwon-si, South Korea). The attenuation system was linear over the sound pressure level range used in the study.

The audible background noise and the piling sounds were monitored via a hydrophone (Model 90.02.01; Labforce, Delft, the Netherlands) and a conditioned charge pre-amplifier (Model CCAMS1000-3; SEAMARCO, Harderwijk, the Netherlands). The output of the pre-amplifier was digitized via the analog-to-digital converter (König Grabber, Model CMP-USBR60; König, Germany) and recorded on the computer (Model 5750G; Acer Aspire) in synchrony with the video images. The output of the pre-amplifier was also fed to an amplified loudspeaker (Model MD5432; Medion, Essen, Germany) so that the operator/data collector in the research cabin could monitor the human-audible part of the background noise during sessions.

Recording Equipment for Sound in the Pool—The SEL distribution of the piling sounds and the background noise in the outdoor pool were

Table 1. The sound exposure level (SEL) in the outdoor pool for each of the six piling sounds. Statistics (power mean, dB mean ± standard deviation [SD]) are presented for the entire pool, and separately for each half of the pool: locations ≤ 6 m and > 6 m from the southwestern end of the pool where the transducer was (see Figure 1). Sound 1 is the full-spectrum playback piling sound; sounds 2 to 6 are reduced-spectrum piling sounds.

		SEL (entire pool) (*n* = 231)		SEL (distance ≤ 6 m) (*n* = 126)		SEL (distance > 6 m) (*n* = 105)	
Sound	Low-pass filter frequency (kHz)	Power mean	dB mean ± SD	Power mean	dB mean ± SD	Power mean	dB mean ± SD
1 (full spectrum)	44.1	135	134 ± 3	137	136 ± 3	132	131 ± 1
2	6.3	136	134 ± 3	138	137 ± 3	132	132 ± 1
3	3.2	135	134 ± 3	138	137 ± 3	132	132 ± 1
4	1.5	135	133 ± 3	137	136 ± 3	132	131 ± 2
5	1.0	135	133 ± 4	137	135 ± 4	131	131 ± 2
6	0.5	133	131 ± 4	135	134 ± 4	129	128 ± 3

measured while the harbor porpoise was not present. The recording and analysis equipment consisted of three hydrophones (Model 8106; Brüel & Kjaer [B&K], Nærum, Denmark), a multichannel high-frequency analyzer (Model PULSE-3560 C; B&K), and a laptop computer with B&K PULSE software (*Labshop*, Version 12.1). The system was calibrated with a pistonphone (Model 4223; B&K). The recordings were made with a 0.01 kHz high-pass filter and at a sample rate of 512 kHz.

Determination of the Sound Exposure Level Used During Playback—During a pilot study, the received SEL of the full-spectrum playback piling sound (sound 1) was gradually increased until it caused the harbor porpoise to respond by increasing her distance to the transducer and respiration rate. At 2-m horizontal offset from the transducer, this unweighted SEL was 140.4 ± 1.4 dB re 1 µPa^{2}s (mean ± SD; measured at three depths, n = 3). The playback piling sound was not distorted, and this SEL was selected for all six piling sounds and was used in all sessions.

Acoustic Characterization of Piling-Sound Sequences—The six piling sounds were characterized in terms of the measured SEL in dB re 1 µPa^{2}s over their duration (t_{90} in s): the time interval between the points when the cumulative SEL (the integrated broadband SPL squared) reached 5 and 95% of the total exposure. Thus, the duration contained 90% of the total energy in the sound (Madsen, 2005). The piling sounds were recorded in the pool. The one-third-octave band spectrum of the unweighted SEL of each of the six piling sounds, measured at 1 m depth and 2 m from the transducer, is shown in Figure 3a. Compared to the full-spectrum playback piling sound 1, the reduced-spectrum piling sounds 2 to 6 had less energy in the high-frequency part of the spectrum.

The one-third-octave band spectrum of the very high-frequency (vhf) cetacean-weighted SEL (SELw; Southall et al., 2019) of each of the six piling sounds, measured at 1 m depth, 2 m from the transducer, is shown in Figure 3b. The weighted spectra were obtained by adding the auditory weighting function for vhf cetaceans (equation 2 in Southall et al., 2019), calculated at the one-third-octave band center frequencies, to the unweighted SEL spectra shown in Figure 3a. The vhf cetacean weighting removed much of the energy in the low-frequency part of the spectrum.

Sound Exposure Levels in the Pool During Playback—To determine the sound distribution in the pool, the SEL of each of the six piling sounds was measured at 77 locations at three depths (0.5, 1.0, and 1.5 m), for one signal per sequence, per piling sound, per location. The distribution of the received unweighted SELs of each sound at the 231 positions in the pool is shown in Figure 4.

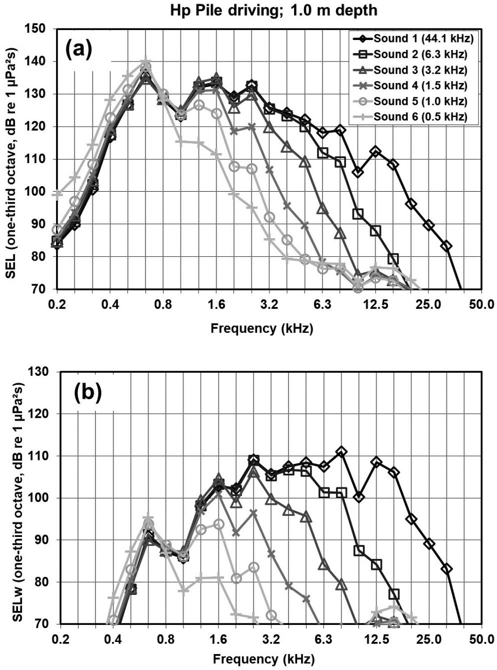

Figure 3. The one-third-octave band spectra of (a) the unweighted SEL and (b) the very high-frequency (vhf) cetacean weighted SELs (SELw; Southall et al., 2019) of each of the six playback piling sounds at six different low-pass filter settings (sound 1 is the full-spectrum playback piling sound; see the legend for low-pass filter frequencies used for sounds 2 to 6). The sounds were measured at 1 m depth, 2 m from the transducer.

The distribution of the received SELw (Southall et al., 2019) is shown in Figure 5; the five reduced-spectrum piling sounds showed a decreasing SELw (Southall et al., 2019). The distributions show that the SEL and SELw at distances ≤ 6 m from the southwestern end of the pool, where the transducer was, are significantly higher than those at distances > 6 m from that end of the pool. There are no systematic differences in SEL with water depth. Tables 1 and 2 show that the unweighted SEL remained approximately constant (Table 1), but the SELw decreased with decreasing bandwidth (lower low-pass filter frequency; Table 2). The variation in the measured levels increases with decreasing bandwidth (lower low-pass filter frequency), probably because narrower bandwidth sounds are more affected by standing waves in the pool.

Video Recording

The harbor porpoise's behavior was filmed from above by a waterproof aerial camera (aerial camera 1, Model 750940; Voltcraft, Conrad

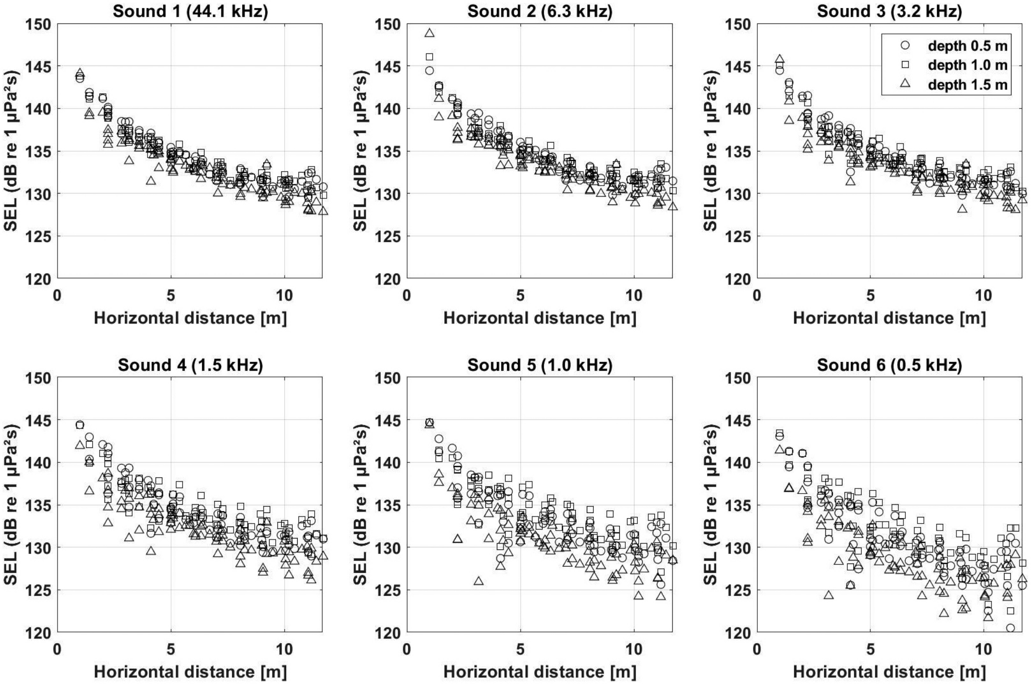

Figure 4. The one-third-octave unweighted SEL distribution in the pool for each of the six playback piling sounds with different low-pass filtering levels, as a function of the horizontal distance to the transducer, measured at three depths (0.5 m: ○, 1.0 m: □, and 1.5 m: Δ; *n* = 77 measurements per depth). Sound 1 is the full-spectrum piling sound; sounds 2 to 6 are reduced-spectrum piling sounds. The variation in SEL increases as the bandwidth is reduced (so that the high-frequency part of the spectrum contains less energy). Most of the unweighted SEL is determined by the peak in the low-frequency part of the spectrum (~0.6 kHz; Figure 3a).

Electronics, Berlin, Germany) with a wide-angle lens and a polarizing filter to prevent saturation of the video image by glare from the water surface. Aerial camera 1 was placed on a pole 8 m above the water surface on the northwestern side of the outdoor pool (Figure 1). The entire surface of the pool was captured on the video image. The image was visible to the operator/data collector and was digitized by an analog-to-digital converter (König Grabber, Model CMP-USBR60) and stored on a laptop computer (Model 5750G; Acer Aspire). The porpoise was also filmed by an action camera (aerial camera 2; GoPro Model Hero3, Woodman Labs, San Mateo, CA, USA) on a pole 5 m above the water surface.

Experimental Procedure

The transducer producing the piling sounds was positioned in the water at the southwestern end of the pool at the start of each day at least one hour before a session began (Figure 1). A session consisted of a baseline period (no sound transmitted) or a test period (playback piling sound transmitted), followed by a pause of random length (1 to 5 h) in which no sound was emitted, followed by either a test or a baseline period. All test and baseline periods lasted 15 minutes. In each session, one baseline and one test period were conducted in random order. One session was conducted per day, five to seven days per week, beginning between 0830 and 1600 h, at random times relative to feeds. During the sessions, only the operator/data collector was allowed in the vicinity of the outdoor pool; he or she sat very still in the research cabin.

In each test period, one of the six piling sounds was transmitted. Each sound was tested in 15 sessions, resulting in 90 sessions (22.5 h of baseline periods and 22.5 h of test periods in all). All 90 sessions were conducted in random order. To prevent masking of the sounds by background noise and to reduce the influence of the weather on the behavior of the harbor porpoise, tests were not carried out during rain or when the wind force was above Beaufort 4. The study was conducted between April and October 2020.

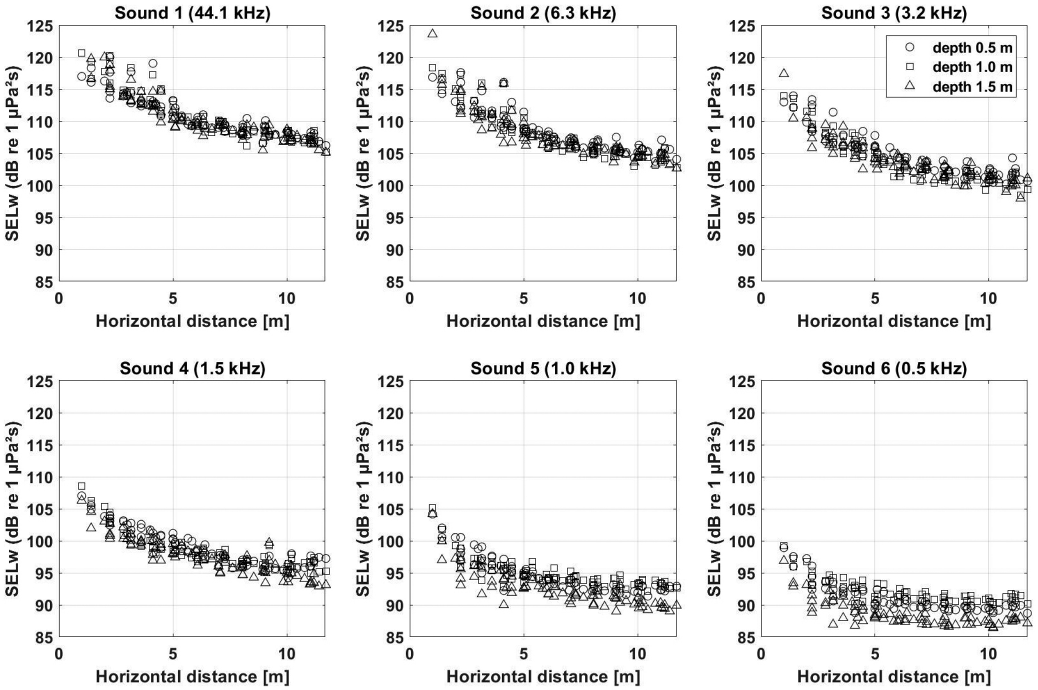

Figure 5. The one-third-octave vhf-cetacean weighted SEL (SELw; Southall et al., 2019) distribution in the pool for each of the six playback piling sounds with different low-pass filtering levels, as a function of the distance to the transducer, measured at three depths (0.5 m: ○, 1.0 m: □, and 1.5 m: Δ; *n* = 77 measurements per depth). Sound 1 is the full-spectrum playback piling sound; sounds 2 to 6 are reduced-spectrum piling sounds. The weighted broadband SEL (SELw) is lower than the unweighted SEL (Figure 4), as much of the energy in piling sounds is in the low-frequency part of the spectrum, and this energy is removed by the vhf cetacean weighting.

Table 2. The SEL in the pool measured with very high-frequency (vhf) cetacean weighting (SELw; Southall et al., 2019) for the full-spectrum playback piling sound 1 (unweighted and weighted) and for each of the five reduced-spectrum piling sounds 2 to 6 (weighted). Statistics (power mean, dB mean, and SD) are presented for the entire pool, and separately for each half of the pool: locations ≤ 6 m and > 6 m from the southwestern end of the pool where the transducer was (Figure 1). Sound 1 is the full-spectrum playback piling sound; sounds 2 to 6 are reduced-spectrum piling sounds.

Sound	Low-pass filter freq. (kHz)	SELw (entire pool) (*n* = 231)		SELw (distance ≤ 6 m) (*n* = 126)		SELw (distance > 6 m) (*n* = 105)	
		Power mean	dB mean ± SD	Power mean	dB mean ± SD	Power mean	dB mean ± SD
1 (unweighted full spectrum)	44.1	135	134 ± 3	137	136 ± 3	132	131 ± 1
1 (weighted full spectrum)	44.1	113	111 ± 3	115	114 ± 3	108	108 ± 1
2	6.3	110	108 ± 4	113	111 ± 3	106	105 ± 1
3	3.2	106	104 ± 3	108	107 ± 3	102	102 ± 1
4	1.5	99	98 ± 3	101	101 ± 2	97	96 ± 1
5	1.0	95	94 ± 3	97	96 ± 3	93	92 ± 1
6	0.5	91	90 ± 2	93	92 ± 3	90	89 ± 2

Response Parameters and Behavioral Data Recording

For each of the six piling sounds, four response parameters—distance from the transducer, respiration rate, relative swimming speed, and number of jumps—were quantified and compared for the paired baseline and test periods within each session.

The harbor porpoise's distance from the transducer was quantified as follows to determine whether she responded to the sounds by swimming away from the transducer. From video camera 2's recordings, the locations where the porpoise surfaced during the baseline and test periods were recorded on a grid superimposed on the computer screen; this allowed compensation for lens distortion. 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 porpoise surfaced was determined, and the center point of the grid square was used to calculate the distance between the porpoise's surfacing location and the transducer via triangulation. 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 and the porpoise could be seen well below the water surface, it was clear that the surfacing locations were a good indication of the porpoise's general swimming area. Respiration took only a fraction of a second, and the porpoise did not linger near the surface. The porpoise's respiration rate (number of breaths in 15 min) in each baseline period was compared to the number during the test period in the same session. The porpoise's relative swimming speed in the test period, relative to the baseline period of that session, was recorded (-1 = slower than the baseline, 0 = similar to the baseline, and 1 = faster than the baseline). Although the porpoise rarely jumped out of the water, all jumps during baseline and test periods were recorded.

Analysis

As the sessions with all piling sounds were conducted in fully random order, order effects were not expected; scatter plots confirmed this expectation. To investigate in detail the harbor porpoise's response to the six piling sounds, paired *t* tests were used to compare her distance from the transducer and respiration rate in baseline periods and associated test periods. For all analyses, assumptions of the tests (independence of observations, normality of differences; Zar, 1999) were conformed to, and the level of significance was 5% (Zar, 1999). Paired *t* tests on the same dependent variables (distance from the transducer and respiration rate) were not considered to be independent, so *p* values were adjusted according to the Holm–Bonferroni method (Quinn & Keough, 2002). Swimming speed and number of jumps were compared without statistical analysis due to their subjective nature and small number of occurrences, respectively.

Results

During baseline periods, the harbor porpoise usually swam large ovals in the outdoor pool. The distance between her surfacing locations and the transducer (mean ± SD: 5.2 ± 0.2 m) and her respiration rate (53 ± 0.6 breaths in 15 min) were similar in all 90 baseline periods, and she never jumped.

In test periods, the harbor porpoise responded to piling sounds 1 to 3 by moving away from the transducer and increasing her respiration rate, and to piling sounds 4 to 6 only by moving away from the transducer (Table 3; Figure 6). In every test period with sounds 1 and 2, the porpoise's swimming speed was higher than in the associated baseline period, and she increased her swimming speed in seven of the 15 test periods with sound 3 (Table 3). In test periods, she never reduced her swimming speed relative to the baseline period. She responded to piling sounds 1 and 2 by jumping occasionally (Table 3).

As the bandwidth of the piling sound decreased (from the full-spectrum playback piling sound 1 to the most narrow-band reduced-spectrum piling sound 6), the harbor porpoise's behavioral response became weaker. In response to sounds 4 to 6, she only moved slightly away from the transducer. Her mean displacement distance, relative to the mean distance to the transducer in the baseline periods, was 4.4 m (± 2.0 m) in response to sound 1; it decreased to 1.4 m (± 2.0 m) for sound 6 (Figure 6a).

Discussion

Evaluation of Study Animal and Playback Piling Sounds

The hearing of the study animal was similar to that of four young male harbor porpoises of similar age (Kastelein et al., 2017) and was thus probably representative of the hearing of harbor porpoises of her age, suggesting that she perceived the sounds as most harbor porpoises would. The effect of a sound on behavior can vary between individuals and may be context-dependent, but the aim of the present study was to compare the effects of six piling sounds on one individual. The differences in response that were observed are valid because the sessions occurred under very low and, more importantly, constant background noise conditions.

Table 3. Results of paired *t* tests to compare the harbor porpoise's distance from the transducer and respiration rate in baseline and associated test periods for six playback piling sounds; see also Figure 6. The sample size for each test is 15. *t* values and adjusted *p* values (Holm–Bonferroni method; Quinn & Keough, 2002) are shown; NS = not significant. In all cases, the mean value for the test period was greater than that for the baseline period. The porpoise responded to piling sounds 1 to 3 by moving away from the transducer and increasing her respiration rate, and to piling sounds 4 to 6 by moving away from the transducer. In every test period with sounds 1 and 2, the porpoise's swimming speed was higher than in the associated baseline period. Of the 15 test periods with sound 3, the porpoise increased her swimming speed in seven of them. No jumps occurred in baseline periods; the total number of jumps recorded in all test periods is shown for each piling sound. The porpoise responded to piling sounds 1 and 2 by jumping occasionally.

Sound	Low-pass filter freq. (kHz)	Distance from transducer (m; test minus baseline)	Respiration rate (Breaths/15-min period; test minus baseline)	Relative swimming speed (Baseline swimming speed = 0)	Number of jumps (In all 15 test periods for each piling sound combined; zero jumps occurred in baseline periods)
1 (full spectrum)	44.1	$t = 8.68, p = 0.000$	$t = 6.71, p = 0.000$	Increased in all test periods	6, spread over four test periods
2	6.3	$t = 21.37, p = 0.000$	$t = 5.71, p = 0.000$	Increased in all test periods	5, in one test period
3	3.2	$t = 8.84, p = 0.000$	$t = 3.30, p = 0.020$	Increased in 7 of 15 test periods	0
4	1.5	$t = 4.95, p = 0.000$	$t = 1.56, p = 0.423$ NS	Unchanged in all test periods	0
5	1.0	$t = 4.02, p = 0.002$	$t = 1.49, p = 0.316$ NS	Unchanged in all test periods	0
6	0.5	$t = 2.73, p = 0.016$	$t = 1.47, p = 0.164$ NS	Unchanged in all test periods	0

After each test period in which the harbor porpoise responded to the sound, her behavior was observed to return to normal immediately; being exposed to the piling sounds at the levels used in this study for 15 minutes had no lasting effect on the porpoise's behavior. A quick return to baseline behavior had been seen in previous acoustic alarm (pinger) and playback pile-driving studies with harbor porpoises (Kastelein et al., 2000, 2001, 2006, 2008a, 2008b, 2013c, 2015a, 2016), and it was the reason for not including a post-test observation period, as was done in a previous pinger study (Kastelein et al., 2000).

Harbor porpoises at sea do not return to piling sites soon after pile driving has stopped. Brandt et al. (2011) observed reduced porpoise acoustic activity within a 2.6 km range from a piling site 24 to 72 hours after sounds stopped, but shorter return times (~6 h) occurred where noise abatement methods such as air bubble screens were employed (Dähne et al., 2017; Brandt et al., 2018). The observed difference may relate to the SEL experienced by the porpoises, which, in the case of harbor porpoises at sea, depends on their distance from the site when piling starts. The SELs in the present study were much lower than those experienced by porpoises in the vicinity of offshore construction sites (~170 to 180 dB re 1 $\mu Pa^2 s$ at 750 m for piling without noise abatement methods; Brandt et al., 2018).

The fact that the very low end of the frequency spectrum (< 0.63 kHz) of piling sounds could not be reproduced in the pool was probably irrelevant for the harbor porpoise in the present study, as the hearing sensitivity of harbor porpoises is low for sounds below 1 kHz (Kastelein et al., 2017; Southall et al., 2019), and they respond predominantly to energy above 1 kHz (Dyndo et al., 2015). The playback piling sounds to which the porpoise was exposed in the present study differ from actual pile-driving sounds at sea, but they have the main characteristics of piling sounds (low-frequency impulsive sounds with a duration of about 100 ms) and are therefore considered relevant.

The four response parameters may have been related to one another. Faster swimming requires a greater oxygen uptake via an increased respiration rate. At higher swimming speeds, harbor porpoises can save energy by leaping clear of the water (Weihs, 2002). While airborne, they are not subjected to underwater noise. Even in response to the most reduced-spectrum piling sounds, the harbor

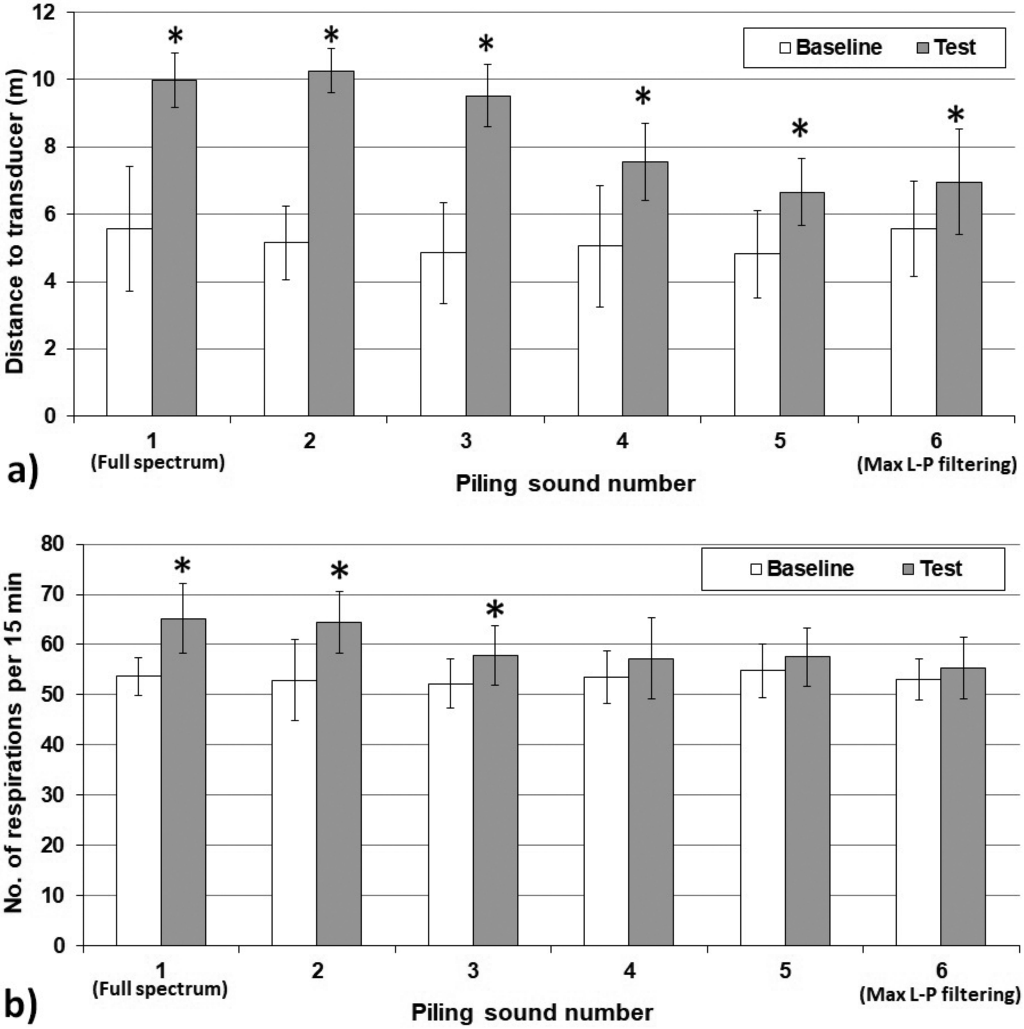

Figure 6. The behavior of the female harbor porpoise during baseline periods without piling sound and in test periods with six playback piling sounds (each at an unweighted mean single-strike SEL of ~135 dB re 1 µPa^{2}s): (a) the distance from the transducer (12 m is the length of the outdoor pool), and (b) the number of respirations per 15 minutes. Each bar indicates mean ± 1 SD (n = 15); an * indicates a significant difference between baseline and test periods (paired t tests; see Table 3). Sound 1 is the full-spectrum playback piling sound, sounds 2 to 6 are reduced-spectrum piling sounds, and sound 6 has maximum low-pass (L-P) filtering.

porpoise was displaced from its usual swimming pathway. Displacement, followed by faster swimming, increased respiration rate, and jumps, suggests that the behavioral responses of the porpoise were cumulative. However, compared to pile driving at sea, the experimental conditions involved lower sound levels and less space, so extrapolation of the results directly to wild harbor porpoises should be done with caution.

Predicting Behavioral Responses of Harbor Porpoises to Pile-Driving Sounds

Exposure to the full-spectrum playback piling sound (sound 1) at an average unweighted broadband SEL in the pool of 135 dB re 1 µPa^{2}s resulted in significant increases in the harbor porpoise's distance from the transducer and respiration rate. However, it may be unrealistic to use captive playback studies to derive an SEL threshold for behavioral responses to unweighted broadband SEL values measured during pile driving at sea (Kastelein et al., 2013c).

The observed reduction in the porpoise's responses to sounds played back at almost equal unweighted broadband SELs, but with decreasing frequency bandwidth (sounds 1 to 6), demonstrates that the frequency content of sounds is an important factor determining the response of harbor porpoises. The decreasing response was aligned with decreasing values of SELw, measured as proposed by Southall et al. (2019). Exposure to pile-driving sound with average SELw values increasing from 90 to 111 dB re 1 µPa^{2}s (corresponding to sounds with increasing bandwidths) in the present study resulted in increasing avoidance of the area close to the transducer, and a significantly increased respiration rate was measured at SELw values of ~100 dB re 1 µPa^{2}s and above. This suggests that it is worth investigating whether the observed relationship between SELw and avoidance behavior of harbor porpoises can be confirmed in field research (see Brandt et al., 2018), and whether a generalized, frequency-weighted response threshold can be established, as conjectured by Tougaard et al. (2015).

In the present study, we applied the auditory weighting function that was proposed by Southall et al. (2019) for application in noise-exposure criteria for temporary and permanent auditory effects, mainly because of the practical benefit of limiting the number of exposure metrics to be determined in environmental impact assessments. The applicability of these specific weighting functions for quantifying behavioral response should be investigated in more detail. However, it is already clear that to improve current predictions of behavioral responses of harbor porpoises to pile-driving sounds, unweighted metrics should be replaced by metrics that include an auditory weighting (Southall et al., 2019).

Mitigation

The present study shows that the high-frequency part of the spectrum of impulsive pile-driving sounds has a relatively large effect on the behavior of harbor porpoises, confirming findings from previous studies with impulsive and non-impulsive sounds. When the same study animal was exposed to impulsive airgun sounds produced behind an air bubble screen, the screen removed the high-frequency part of the spectrum and thus reduced the porpoise's response to the sounds (Kastelein et al., 2019a). The startle responses of harbor porpoises to 1 to 2 kHz and 6 to 7 kHz sweeps with high-frequency harmonics are also stronger than their responses to the same signals without harmonics (Kastelein et al., 2012). Therefore, to reduce the impact of impulsive sounds (and other broadband sounds) on harbor porpoises in the wild, reduction of the energy in the high-frequency part of the spectrum should be the priority. Removal of only this high-frequency energy in mitigation would make mitigation more feasible and affordable. Air bubble screens are already in use in some countries in which offshore pile driving occurs, and they have proved to be very effective in reducing radiated noise above 1 kHz (Dähne et al., 2017; Tougaard & Dähne, 2017).

Acknowledgments

We thank assistant Suzanne Cornelisse and the following students and volunteers for their help with the study: Matthijs Marsman, Luna Korsuize, Femke Kuiphof, Pepijn Degger, Stephanie de Ruijter, Manouk Vermeulen, Ramona van Alphen, Irna Huisjes, Yarnick Herben, and Renee de Waard. We thank Rob Triesscheijn (†) for making Figure 1, and Bert Meijering (Topsy Baits) for providing space for the SEAMARCO Research Institute. Erwin Jansen (TNO) did the acoustic measurements. We thank Arie Smink for the construction and maintenance of the electronic equipment. We also thank Nancy Jennings (Dotmoth.co.uk) for the statistical analysis and comments on the manuscript, and John Terhune (University of New Brunswick, Canada) and two anonymous reviewers for their valuable constructive comments on this manuscript. Funding for this project was obtained from (1) the Netherlands Ministry of Infrastructure and Water Management (Case Number 31160611)—we thank Inger van den Bosch, Sarah Marx, Ingeborg van Splunder, and Niels Kinneging for their guidance on behalf of the Dutch Wind at Sea Ecological Program (WOZEP); and (2) Eneco (Order Number 4500730976/2142)—we thank Marin van Regteren for her guidance on behalf of Eneco. The harbor porpoise was tested under authorization of the Netherlands Ministry of Economic Affairs with Endangered Species Permit FF/75A/2016/031. The porpoise was rented from Dolfinarium Harderwijk (part of the ASPRO group).

Literature Cited

Ainslie, M. A. (2010). *Principles of sonar performance modelling*. Springer Praxis. https://doi.org/10.1007/978-3-540-87662-5

Bailey, H., Senior, B., Simmons, D., Rusin, J., Picken, G., & Thompson, P. M. (2010). Assessing underwater noise levels during pile-driving at an offshore windfarm and its potential effects on marine mammals. *Marine Pollution Bulletin*, *60*, 888-897. https://doi.org/10.1016/j.marpolbul.2010.01.003

Bellmann, M. A., Brinkmann, J., May, A., Wendt, T., Gerlach, S., & Remmers, P. (2020). *Underwater noise during the impulse pile-driving procedure: Influencing factors on pile-driving noise and technical possibilities to comply with noise mitigation values*. Supported by the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (Bundesministerium für Umwelt, Naturschutz und nukleare Sicherheit [BMU]), FKZ UM16 881500. Commissioned and managed by the Federal Maritime and Hydrographic Agency (Bundesamt für Seeschifffahrt und Hydrographie [BSH]), Order No. 10036866.

Brandt, M. J., 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. *Marine Ecological Progress Series*, *421*, 205-216. https://doi.org/10.3354/meps08888

Brandt, M. J., Dragon, A. C., Diederichs, A., Bellmann, M. A., Wahl, V., Piper, W., Nabe-Nielsen, J., & Nehls, G. (2018). Disturbance of harbour porpoises during construction of the first seven offshore wind farms in Germany. *Marine Ecological Progress Series*, *596*, 213-232. https://doi.org/10.3354/meps12560

Dähne, M., Tougaard, J., Carstensen, J., Rose, A., & Nabe-Nielsen, J. (2017). Bubble curtains attenuate noise from offshore wind farm construction and reduce temporary habitat loss for harbour porpoises. *Marine Ecological Progress Series*, *580*, 221-237. https://doi.org/10.3354/meps12257

Dähne, M., Gilles, A., Lucke, K., Peschko, V., Adles, S., Krügel, K., Sundermeyer, J., & Siebert, U. (2013). Effects of pile-driving on harbour porpoises (*Phocoena phocoena*) at the first offshore windfarm in Germany. *Environmental Research Letters*, *8*, 1-16. https://doi.org/10.1088/1748-9326/8/2/025002

Dyndo, M., Wiśniewska, D. M., Rojano-Doñate, L., & Madsen, P. T. (2015). Harbour porpoises react to low levels of high frequency vessel noise. *Scientific Reports*, *5*, 11083. https://doi.org/10.1038/srep11083

Graham, I. M., Merchant, N. D., Farcas, A., Barton, T. R., Cheney, B., Bono, S., & Thompson, P. M. (2019). Harbour porpoise responses to pile-driving diminish over time. *Royal Society Open Science*, *6*, 190335. https://doi.org/10.1098/rsos.190335

Haelters, J., Dulière, V., Vigin, L., & Degraer, S. (2014). Towards a numerical model to simulate the observed displacement of harbour porpoises *Phocoena phocoena* due to pile driving in Belgian waters. *Hydrobiologia*, *756*, 105-116. https://doi.org/10.1007/s10750-014-2138-4

Kastelein, R. A., Helder-Hoek, L., & Van de Voorde, S. (2017). Hearing thresholds of a male and a female harbor porpoise (*Phocoena phocoena*). *The Journal of the Acoustical Society of America*, *142*, 1006-1010. https://doi.org/10.1121/1.4997907

Kastelein, R. A., Hoek, L., & de Jong, C. A. F. (2011). Hearing thresholds of a harbor porpoise (*Phocoena phocoena*) for sweeps (1-2 kHz and 6-7 kHz bands) mimicking naval sonar signals. *The Journal of the Acoustical Society of America*, *129*, 3393-3399. https://doi.org/10.1121/1.3569739

Kastelein, R. A., Gransier, R., Marijt, M. A. T., & Hoek, L. (2015a). Hearing frequencies of a harbor porpoise (*Phocoena phocoena*) temporarily affected by played back offshore pile driving sounds. *The Journal of the Acoustical Society of America*, *137*, 556-564. https://doi.org/10.1121/1.4906261

Kastelein, R. A., Gransier, R., van den Hoogen, M., & Hoek, L. (2013a). Brief behavioral response threshold levels of a harbor porpoise (*Phocoena phocoena*) to five helicopter dipping sonar signals (1.33 to 1.43 kHz). *Aquatic Mammals*, *39*(2), 162-173. https://doi.org/10.1578/AM.39.2.2013.162

Kastelein, R. A., Helder-Hoek, L., Covi, J., & Gransier, R. (2016). Pile driving playback sounds and temporary threshold shift in harbor porpoises (*Phocoena phocoena*): Effect of exposure duration. *The Journal of the Acoustical Society of America*, *139*, 2842-2851. https://doi.org/10.1121/1.4948571

Kastelein, R. A., Hoek, L., de Jong, C. A. F., & Wensveen, P. J. (2010). The effect of signal duration on the underwater detection thresholds of a harbor porpoise (*Phocoena phocoena*) for single frequency-modulated tonal signals between 0.25 and 160 kHz. *The Journal of the Acoustical Society of America*, *128*, 3211-3222. https://doi.org/10.1121/1.3493435

Kastelein, R. A., Hoek, L., Gransier, R., & de Jong, C. A. F. (2013b). Hearing thresholds of a harbor porpoise (*Phocoena phocoena*) for playbacks of multiple pile driving strike sounds. *The Journal of the Acoustical Society of America*, *134*, 2302-2306. https://doi.org/10.1121/1.4817842

Kastelein, R. A., van den Belt, I., Gransier, R., & Johansson, T. (2015b). Behavioral responses of a harbor porpoise (*Phocoena phocoena*) to 24.5-25.5 kHz sonar down-sweeps with and without side bands. *Aquatic Mammals*, *41*(4), 400-411. https://doi.org/10.1578/AM.41.4.2015.400

Kastelein, R. A., van Heerden, D., Gransier, R., & Hoek, L. (2013c). Behavioral responses of harbor porpoise (*Phocoena phocoena*) to playbacks of broadband pile driving sounds. *Marine Environmental Research*, *92*, 206-214. https://doi.org/10.1016/j.marenvres.2013.09.020

Kastelein, R. A., Verboom, W. C., Jennings, N., & de Haan, D. (2008a). Behavioral avoidance threshold level of a harbor porpoise (*Phocoena phocoena*) for a continuous 50 kHz pure tone (L). *The Journal of the Acoustical Society of America*, *123*, 1858-1861. https://doi.org/10.1121/1.2874557

Kastelein, R. A., de Haan, D., Vaughan, N., Staal, C., & Schooneman, N. M. (2001). The influence of three acoustic alarms on the behaviour of harbour porpoises (*Phocoena phocoena*) in a floating pen. *Marine Environmental Research*, *52*, 351-371. https://doi.org/10.1016/S0141-1136(01)00090-3

Kastelein, R. A., Jennings, N., Verboom, W. C., de Haan, D., & Schooneman, N. M. (2006). Differences in the response of a striped dolphin (*Stenella coeruleoalba*) and a harbour porpoise (*Phocoena phocoena*) to an acoustic alarm. *Marine Environmental Research*, *61*, 363-378. https://doi.org/10.1016/j.marenvres.2005.11.005

Kastelein, R. A., Schop, J., Gransier, R., Steen, N., & Jennings, N. (2014). Effect of series of 1-2 kHz and 6-7 kHz up-sweeps and down-sweeps on the behavior of a harbor porpoise (*Phocoena phocoena*). *Aquatic Mammals*, *40*(3), 232-242. https://doi.org/10.1578/AM.40.3.2014.232

Kastelein, R. A., Steen, N., Gransier, R., Wensveen, P. J., & de Jong, C. A. F. (2012). Threshold received sound pressure levels of single 1-2 kHz and 6-7 kHz up-sweeps and down-sweeps causing startle responses in a harbor porpoise (*Phocoena phocoena*). *The Journal of the Acoustical Society of America*, *131*, 2325-2333. https://doi.org/10.1121/1.3682032

Kastelein, R. A., Verboom, W. C., Jennings, N., de Haan, D., & van der Heul, S. (2008b). The influence of 70 and 120 kHz tonal signals on the behavior of harbor porpoises (*Phocoena phocoena*) in a floating pen. *Marine Environmental Research*, *66*, 319-326. https://doi.org/10.1016/j.marenvres.2008.05.005

Kastelein, R. A., von Benda-Beckmann, A. M., Lam, F-P. A., Jansen, E., & de Jong, C. A. F. (2019a). Effect of a bubble screen on the behavioral responses of captive harbor porpoises (*Phocoena phocoena*) exposed to airgun sounds. *Aquatic Mammals*, *45*(6), 706-716. https://doi.org/10.1578/AM.45.6.2019.706

Kastelein, R. A., Huijser, L. A. E., Cornelisse, S., Helder-Hoek, L., Jennings, N., & de Jong, C. A. F. (2019b). Effect of pile-driving playback sound level on fish-catching efficiency in harbor porpoises (*Phocoena phocoena*). *Aquatic Mammals*, *45*(4), 398-410. https://doi.org/10.1578/AM.45.4.2019.398

Kastelein, R. A., Rippe, H. T., Vaughan, N., Schooneman, N. M., Verboom, W. C., & de Haan, D. (2000). The effect of acoustic alarms on the behavior of harbor porpoises (*Phocoena phocoena*) in a floating pen. *Marine Mammal Science*, *16*, 46-64. https://doi.org/10.1111/j.1748-7692.2000.tb00903.x

Madsen, P. T. (2005). Marine mammals and noise: Problems with root mean square sound pressure levels for transients. *The Journal of the Acoustical Society of America*, *117*, 3952-3957. https://doi.org/10.1121/1.1921508

Martin, S. B., Lucke, K., & Barclay, D. R. (2020). Techniques for distinguishing between impulsive and non-impulsive sound in the context of regulating sound exposure for marine mammals. *The Journal of the Acoustical Society of America*, *147*(4), 2159-2176. https://doi.org/10.1121/10.0000971

National Research Council (NRC). (2005). *Marine mammal populations and ocean noise: Determining when noise causes biologically significant effects*. The National Academies Press. 126 pp.

Nowacek, D. P., Thorne, L. H., Johnston, D. W., & Tyack, P. L. (2007). Responses of cetaceans to anthropogenic noise. *Mammal Review*, *37*, 81-115. https://doi.org/10.1111/j.1365-2907.2007.00104.x

Quinn, G. P., & Keough, M. J. (2002). *Experimental design and data analysis for biologists*. Cambridge University Press. 537 pp. https://doi.org/10.1017/CBO9780511806384

Richardson, W. J., Greene, C. R., Jr., Malme, C. I., & Thomson, D. H. (1995). *Marine mammals and noise*. Academic Press. 576 pp. https://doi.org/10.1016/B978-0-08-057303-8.50011-2

Southall, B. L., Finneran, J. J., Reichmuth, C., Nachtigall, P. E., Ketten, D. R., Bowles, A. E., Ellison, W. T., Nowacek, D. P., & Tyack, P. L. (2019). Marine mammal noise exposure criteria: Updated scientific recommendations for residual hearing effects. *Aquatic Mammals*, *45*(2), 125-232. https://doi.org/10.1578/AM.45.2.2019.125

Tougaard, J., & Dähne, M. (2017). Why is auditory frequency weighting so important in regulation of underwater noise? *The Journal of the Acoustical Society of America*, *142*, EL415-EL420. https://doi.org/10.1121/1.5008901

Tougaard, J., Wright, A. J., & Madsen, P. T. (2015). Cetacean noise criteria revisited in the light of proposed exposure limits for harbour porpoises. *Marine Pollution Bulletin*, *90*, 196-208. https://doi.org/10.1016/j.marpolbul.2014.10.051

Tougaard, J., Carstensen, J., Teilmann, J., Skov, H., & Rasmussen, P. (2009). Pile driving zone of responsiveness extends beyond 20 km for harbor porpoises (*Phocoena phocoena*) (L.). *The Journal of the Acoustical Society of America*, *126*, 11-14. https://doi.org/10.1121/1.3132523

Weihs, D. (2002). Dynamics of dolphin porpoising revisited. *Integrated and Comparative Biology*, *42*, 1071-1078. https://doi.org/10.1093/icb/42.5.1071

Wright, A. J., Soto, N. A., Baldwin, A. L., Bateson, M., Beale, C. M., Clark, C., Deak, T., Edwards, E. F., Fernández, A., Godinho, A., Hatch, L. T., Kakuschke, A., Lusseau, D., Martineau, D., Romero, M. L., Weilgart, L. S., Wintle, B. A., Notarbartolo di Sciara, G., & Martin, V. (2007). Do marine mammals experience stress related to anthropogenic noise? *International Journal of Comparative Psychology*, *20*, 274-316.

Zar, J. H. (1999). *Biostatistical analysis* (4th ed.). Prentice Hall. 718 pp.