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Effect of Impact Pile-Driving Playback Sound on Harbor Seal (*Phoca vitulina*) Behavior: Dose-Response Relationship and Frequency Weighting

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Abstract

Two experiments were conducted to quantify the behavioral response of harbor seals (*Phoca vitulina*) to impulsive underwater sounds as produced during impact pile driving for offshore wind turbines. In Experiment 1 (dose-response relationship), two female harbor seals in a quiet pool were exposed to playbacks of minimally filtered pile-driving sounds (46 strikes/min) recorded at one location in the North Sea, at seven unweighted broadband single-strike sound exposure levels (SELss) at 6 dB steps between 125 and 161 dB re 1 µPa^{2}s. Considering the dose-response relationship as expressed by the harbor seals' position and their jumps out of the water, the onset of behavioral response occurred at 131 dB re 1 µPa^{2}s in seal F01 and at 137 dB re 1 µPa^{2}s in seal F02. The response was very clear in both harbor seals ≥ 143 dB re 1 µPa^{2}s. Experiment 2 (effect of weighting) assessed whether sound levels used in predictions of harbor seal behavioral responses to pile-driving sounds should be frequency-weighted to reflect hearing sensitivity. The seals were exposed for 15 min to the minimally filtered pile-driving playback sound (PS), a low-pass filtered version (LP, filtered at 0.5 kHz), and a high-pass filtered version (HP, filtered at 4 kHz), with the same mean received unweighted broadband SELss (161 dB re 1 µPa^{2}s). With the auditory weighting function for Phocidae in water applied, SELss were 156 (PS), 151 (LP), and 161 (HP) dB re 1 µPa^{2}s. Both seals responded to all three pile-driving sounds but were most affected by the PS and HP sounds, showing that the high-frequency components of pile-driving playback sounds caused most of the behavioral effects. The second experiment showed that weighting of SELss is useful when setting underwater sound criteria for behavioral responses in Phocidae, as weighted SELss was a better predictor of behavioral response than unweighted SELss. The results indicate that the design of noise mitigation measures for harbor seals should focus on the reduction of the high-frequency components of impact pile-driving sounds.

Key Words: anthropogenic sound, behavior, impact pile driving, offshore wind farm, phocid, weighting

Introduction

As part of the transition towards sustainable energy sources, wind turbines are being deployed worldwide. Many offshore wind turbines are installed in relatively shallow coastal waters, which are generally already heavily used by humans for activities such as transportation, fishing, recreation, and oil and gas exploration and extraction. Although alternative methods of attaching the wind turbines to the sea floor exist, wind turbine installation commonly involves percussive pile driving that produces high-amplitude impulsive sounds. The duration, spectrum, and level of these impulsive sounds depend on the characteristics of the pile, hammer, and pile-driving energy; on the distance from the pile at which the sound is measured; and on propagation conditions (Ainslie et al., 2009; Andersen et al., 2013; Merchant et al., 2016).

Marine fauna may experience negative impacts of pile-driving sounds. One marine mammal species occurring in large numbers in the temperate and Arctic coastal areas of many countries in the Northern Hemisphere is the harbor seal (*Phoca vitulina*; Burns, 2009). The geographic range of the harbor seal overlaps with locations in which wind farms have been, or will be, built. Harbor seals have sensitive underwater hearing, and they have functional underwater hearing over a wide frequency range (Kastelein et al., 2009b). Sound is important for harbor seals 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). Pile-driving sounds may reduce the efficiency of these activities by auditory masking, by causing temporary or permanent hearing threshold shifts (TTS and PTS), or by causing behavioral changes (National Research Council [NRC], 2003).

Some studies have been conducted with harbor seals and pile-driving sounds. Kastelein et al. (2013a) determined the hearing threshold of two harbor seals for playbacks of pile-driving sounds, and Kastelein et al. (2018) determined the susceptibility of harbor seal hearing to pile-driving sounds by measuring TTS after exposure to played-back pile-driving sounds. These studies provided information on the unweighted single-strike sound exposure level (SELss) above which harbor seals can detect pile-driving sounds, and the cumulative sound exposure level above which hearing sensitivity becomes temporarily reduced. Observations of wild harbor seals at sea show that they respond behaviorally to offshore pile-driving sounds (Edrén et al., 2010; Skeate et al., 2012; Russell et al., 2016; Whyte et al., 2020). Seal abundance can be significantly reduced up to 25 km from a pile-driving site (Hastie et al., 2015; Russell et al., 2016). To model the effect of impact pile-driving sounds on harbor seal behavior (as well as on their hearing; Whyte et al., 2020), it is important to discover at what broadband SELss pile-driving sounds affect the behavior of harbor seals. Such information is required to generate input parameters (e.g., estimates of numbers of animals likely to respond) for population-effect models, such as Interim Population Consequences of Disturbance (PCoD; King et al., 2015). The information can also be used to regulate sound appropriately by using simple measures (Juretzek et al., 2021).

Noise exposure criteria based on predictions of the onset of TTS and PTS in marine mammals that take known hearing sensitivity into account (or expected sensitivity for species of which the hearing sensitivity is unknown) have been proposed by Southall et al. (2019). The criteria are expressed in terms of frequency-weighted SELss for species groups with assumed similar hearing detection thresholds (audiograms; Southall et al., 2019). Figure 1 shows the auditory weighting function for "phocid carnivores in water" (PCW; Southall et al., 2019, p. 134), illustrating that the contribution of sound below ~0.6 kHz to the weighted SELss is reduced by more than 10 dB.

Severity scales for behavioral responses to sound exposure by free-ranging marine mammals were proposed by Southall et al. (2021), but they have not been linked to received sound levels for the different species groups. It is not clear whether or

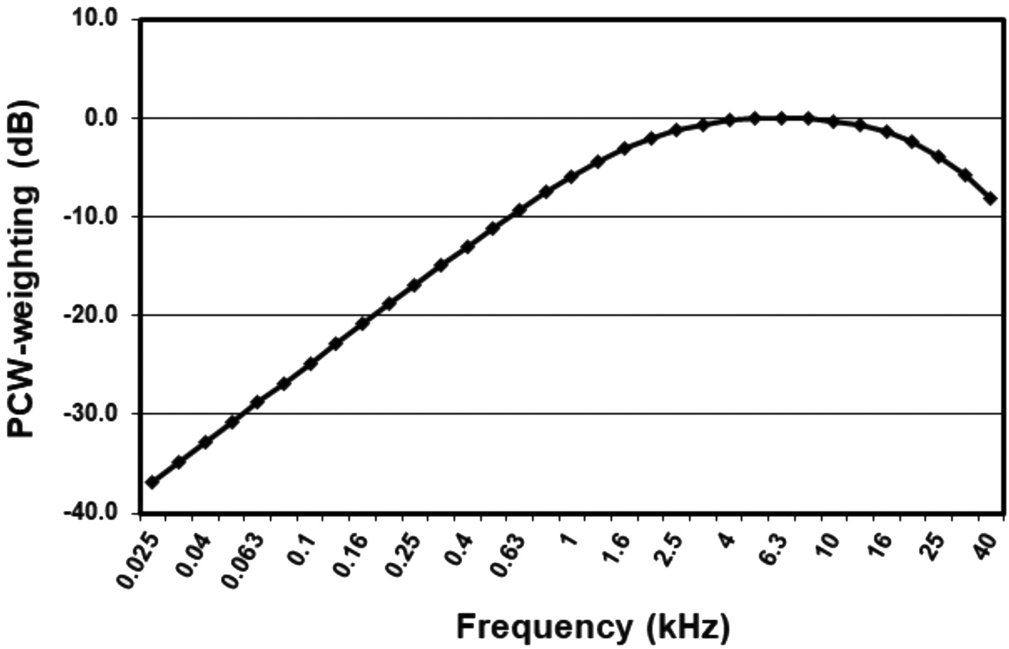


Figure 1. The auditory weighting function for "phocid carnivores in water" (PCW, Southall et al., 2019, p. 134), calculated at one-third octave (base-10) center frequencies

not auditory frequency weighting of pile-driving sounds is likely to improve predictions of behavioral responses, or whether auditory weighting will be required to set safety criteria and develop mitigation measures. If auditory frequency weighting is to be useful for predicting behavioral responses to sound exposure (Verboom & Kastelein, 2005; Tougaard et al., 2014; Kastelein et al., 2022), relationships between frequency-weighted SELs and behavioral responses need to be quantified. We evaluated these relationships and the value of frequency weighting for the harbor seal.

In Experiment 1, our goal was to establish a dose-response behavioral relationship for harbor seals and one spectrum of pile-driving sounds. In Experiment 2, we investigated whether behavioral response in the harbor seal is better predicted or explained by frequency-weighted metrics (Southall et al., 2019) or by unweighted metrics. With the information from both experiments, combined with information on pile-driving sound source levels, background noise, local propagation conditions, and changes in the pile-driving sound's spectrum over distance, the extent of the area around a pile-driving site in which the behavior of harbor seals is likely to be influenced can be estimated, and mitigation measures can be optimized.

Methods

Study Animals and Study Area

The study animals were two healthy adult female harbor seals, identified as F01 and F02. They were 14 y old during data collection, and their hearing was representative of wild conspecifics (Kastelein et al., 2009a, 2009b). The two seals had very similar girths and body weights that fluctuated seasonally between ~45 kg in summer and ~62 kg in winter. Details of their husbandry and food rations are provided by Kastelein et al. (2019a). The seals had participated in previous acoustic behavioral response studies (Kastelein et al., 2015a, 2015b, 2017b).

The study was conducted at the SEAMARCO Research Institute, The Netherlands, in an outdoor seawater pool (8 × 7 m and 2 m deep; for details, see Kastelein et al., 2019b) with two haul-out platforms (Figure 2). During the experiments, both harbor seals were together in the pool.

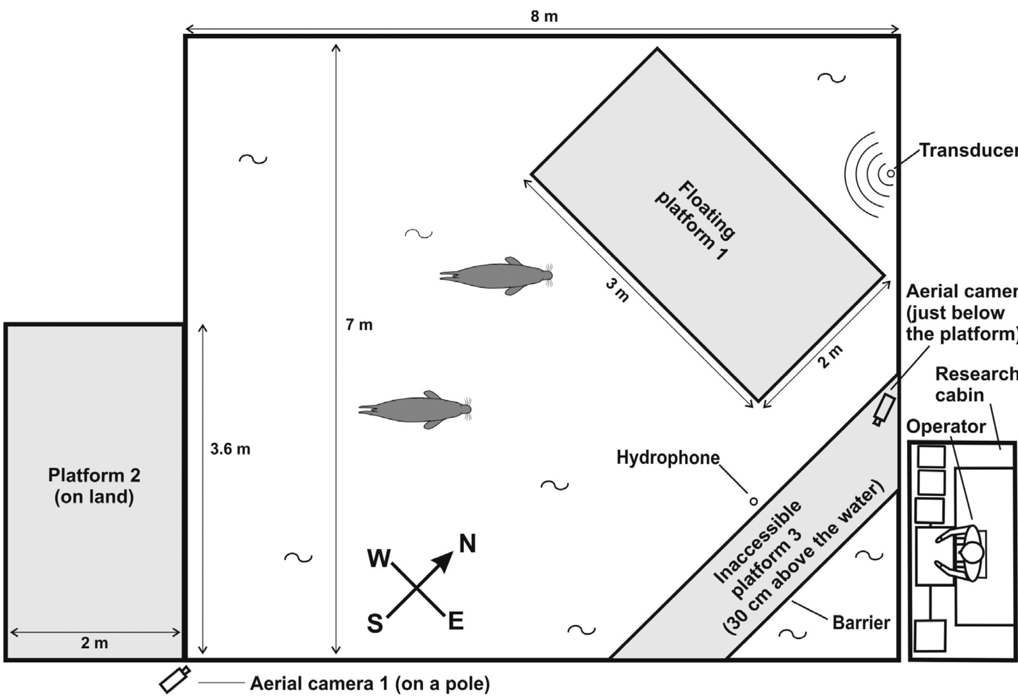


Figure 2. Top scale view of the outdoor pool where the study was conducted, showing the harbor seals (*Phoca vitulina*), the location of the two aerial cameras, the underwater transducer emitting the pile-driving sounds at 1.5 m depth, and the hydrophone at 1 m depth (used to listen to the pile-driving sounds and ambient noise). Also shown is the research cabin that housed the video and audio equipment and the operator. A barrier below the platform prevented the seals from reaching the triangular part of the pool in the lower right-hand corner. Platforms 1 and 2 were accessible haul-out areas; platform 1 was floating but fixed in place.

Terminology, Recording, and Monitoring of Sounds

Acoustical terminology follows ISO 18405 (International Organization for Standardization [ISO], 2017). SELss was selected as the appropriate measure of magnitude of sound exposure for consistency with previous studies and with legislation in some countries bordering the geographic range of the harbor seal.

Ambient noise was measured, and the pile-driving playback sounds were calibrated before, during, and after the study period while the harbor seals were not present in the pool as well as under test conditions (see below and Kastelein et al., 2019a, 2019b). The recording and analysis equipment consisted of three hydrophones (Brüel & Kjaer [B&K] Model 8106; B&K, Virum, Denmark), a multichannel high-frequency analyzer (B&K Model Lan-XI Type 3050), and a laptop computer with B&K *PULSE* software (*LabShop*, Version 20). The system was calibrated with a pistonphone (B&K Model 4223), and the recordings were made with a 22.4 Hz high-pass filter (incorporated into the B&K Lan-XI analyzer) at a sample rate of 131 kHz.

Under test conditions (i.e., only the operator allowed within 15 m of the pool and required to remain stationary, water circulation system off, no rain, and wind speed similar to Beaufort Sea State 4 or below), the ambient noise in the pool was very low and fairly constant in amplitude due to the sheltered location of the pool (Figure 3). During sessions, the human-audible ambient noise and the pile-driving sounds were monitored via a hydrophone (Labforce Model 90.02.01; Labforce Inc., Delft, the Netherlands) and a conditioned charge pre-amplifier (B&K Model 2635). The output of the pre-amplifier was digitized via an analog-to-digital converter (Zolid Video Grabber, Smart Group, Taiwan) and recorded on a laptop computer (Medion Model MD98110 PLU782; Aldi, Essen, Germany) in synchrony with the video images. The pre-amplifier output was also fed to an amplified loudspeaker (Medion Model MD5432) so that the operator in the research cabin could monitor the pile-driving sound and human-audible ambient noise during sessions. Via a microphone, the operator added the date, time, experiment, session number, and sound level or pile-driving sound being tested to the video recording at the start of each session.

Playback Sounds in Experiment 1 (Dose-Response Relationship)

Offshore pile-driving sounds were recorded in the North Sea, 100 m from the sound source where a foundation pile was being driven into

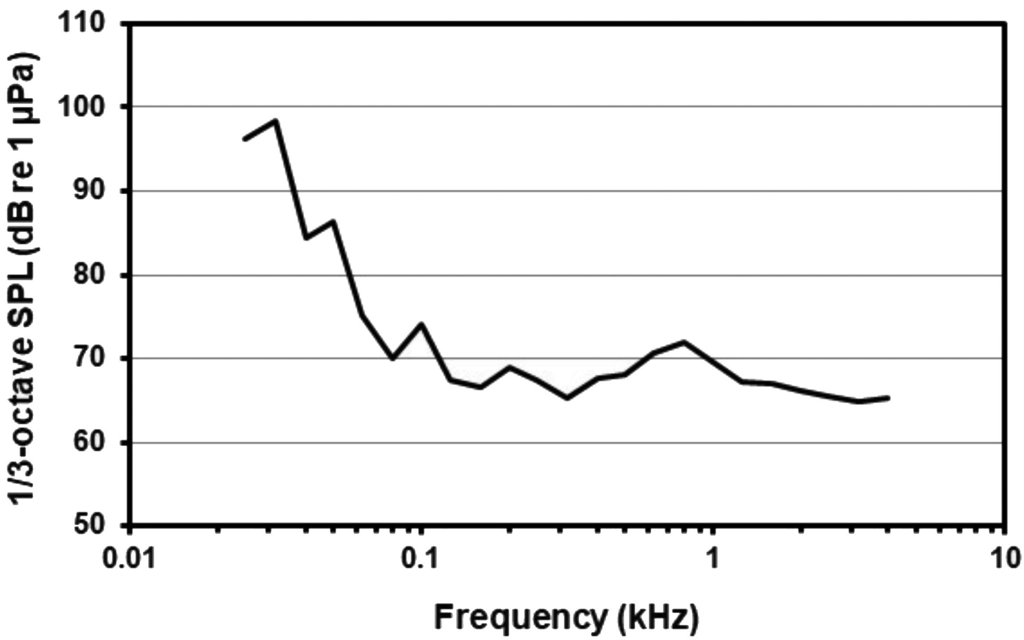


Figure 3. The underwater ambient sound pressure level (SPL) in the harbor seal pool under test conditions. The level is low; for most of the spectrum it is below the level measured during Beaufort Sea State 0 in the open sea. Above 3.2 kHz, the ambient noise level could not be measured because it was below the self-noise of the recording system.

the seabed for a wind turbine in the Dutch offshore wind farm "Egmond aan Zee." Pile-driving sound in the recordings was much louder than the background noise. A WAV file was made of a series of five consecutive pile-driving strike sounds with a strike rate of 46 strikes/min. The recording was sampled at 88.2 kHz sample frequency. For the playback studies, the original sounds were minimally filtered. They were filtered (2nd order Butterworth; 24 dB/octave roll-off) at 0.5 kHz because lower frequencies could not be reproduced efficiently due to transducer characteristics and the limited water depth in the pool (2 m; Kastelein et al., 2013a). The upper frequency of the playback sound was limited to about 9 kHz by the transducer characteristics. The resulting pile-driving playback sound recording (> 0.5 kHz), which had been used in previous acoustic studies (Kastelein et al., 2013a, 2013b), was used in Experiment 1 and is abbreviated here as PS (the minimally filtered pile-driving playback sound). The WAV file was looped so that the strikes were played back at a rate of 46/min for the 15-min test period duration.

Before Experiment 1, the maximum level at which the single strikes could be produced without distortion was determined; this single-strike sound exposure level (SELss) was chosen as the highest level used in Experiment 1 (in the expectation that this level would elicit a behavioral response). In each of the following sessions in a pilot study, the sound pressure level (SPL), and thus the SELss, was reduced by 6 dB until no behavioral response was observed. This was done to find a rough behavioral response threshold SELss. During Experiment 1, the PS sequences were produced at mean received unweighted broadband SELss of 125, 131, 137, 143, 149, 155, and 161 dB re 1 µPa^{2}s (power averaged over all positions in the pool, standard deviation [SD] ~2.5 dB, n = 99 per level; Table 1). The seven one-third octave (base-10) band unweighted SELss spectra of the PS pile-driving playback sound, measured at 1 m depth and 2 m from the transducer, are shown in Figure 4.

Playback Sounds in Experiment 2 (Effect of Weighting)

To investigate effects of frequency-weighting, three pile-driving sounds were played back at the same unweighted broadband SELss. Applying Southall et al.'s (2019) auditory weighting function for PCW (phocid carnivores in water) to these sounds resulted in different values of the frequency-weighted broadband SELss (Table 1; Figure 5). Comparison of the harbor seals' behavioral response to these three sounds was expected to reveal whether the response was better predicted by

Table 1. Unweighted and weighted single-strike sound exposure levels (SELss) for each of the three pile-driving playback sounds. For Experiment 1, the seven levels of the pile-driving playback sound PS (minimally filtered) are shown. For both experiments, the weighed SELss, with the auditory weighting function for phocid carnivores in water (Southall et al., 2019) applied, are also shown. Statistics are for the entire pool (power mean; n = 99 measurement points in the pool). The minimally filtered pile-driving playback sound PS was used in Experiments 1 and 2. In Experiment 2, pile-driving sound LP is a low-frequency pile-driving playback sound with a low-pass filter frequency of 0.5 kHz, and pile-driving sound HP is a high-frequency pile-driving playback sound with a high-pass filter frequency of 4 kHz. *For the PS sound, the original recording was high-pass filtered at 0.5 kHz and low-pass filtered to about 9 kHz by the response of the underwater transducer. The LP and HP pile-driving sounds were produced by further filtering the original recording.

Pile-driving playback sound	Experiment	Filter*	Unweighted SELss (dB re 1 µPa^{2}s) Power mean (n = 99)	Weighted SELss (dB re 1 µPa^{2}s) Power mean (n = 99)
PS	1	Minimal	125	120
PS	1	Minimal	131	126
PS	1	Minimal	137	132
PS	1	Minimal	143	138
PS	1	Minimal	149	144
PS	1	Minimal	155	150
PS	1 & 2	Minimal	161	156
LP	2	Low-pass, 0.5 kHz	161	151
HP	2	High-pass, 4 kHz	161	161

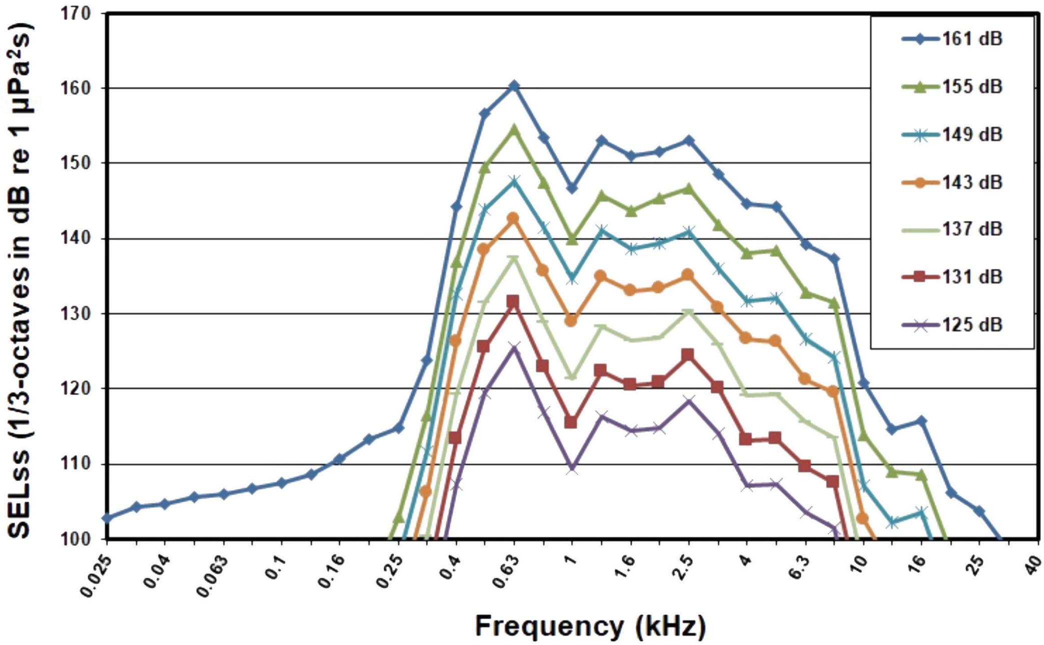


Figure 4. The one-third octave (base-10) single-strike sound exposure levels (SELss) of the pile-driving playback sound PS (minimally filtered) used in Experiment 1 (dose-response relationship). The sounds were measured in the pool at 1 m depth, 2 m from the transducer. The pile-driving playback sounds were recorded in the WAV file format. The recorded sounds were high-pass filtered at 0.5 kHz to remove frequencies that could not be reproduced well by the underwater transducer, but the frequency-weighted metrics for "phocid carnivores in water" (Southall et al., 2019, p. 134; Figure 1) were not applied.

weighted or by unweighted metrics: if the response to exposures with different frequency content at the same unweighted SELss was similar, weighting would be unnecessary for the prediction of behavioral responses.

Pile-driving playback sound PS (the playback sound that was also used in Experiment 1) was played back at an unweighted broadband SELss of 161 dB re 1 µPa^{2}s (power mean). The weighted SELss of PS was 156 dB re 1 µPa^{2}s (this playback sound was high-pass filtered with a 2nd-order Butterworth filter at 0.5 kHz, so it was not an exact representation of sounds recorded at sea).

For Experiment 2, the pile-driving playback sound PS was used alongside two reduced-spectrum versions: (1) the low-frequency pile-driving sound (LP) was produced by low-pass filtering (2nd order Butterworth, 24 dB/octave roll-off) the pile-driving sound with a filter frequency at 0.5 kHz; Figure 5a); and (2) the high-frequency pile-driving sound (HP) was produced by high-pass filtering (2nd order Butterworth, 24 dB/octave roll-off) at 4 kHz (Figure 5a). The amplitudes of pile-driving sounds LP and HP were adjusted to keep the unweighted broadband SELss equal to that of the PS sound (Table 1). The three pile-driving sounds were played back at the same unweighted SELss: 161 dB re 1 µPa^{2}s. The weighted SELss of LP was 151 dB re 1 µPa^{2}s; and that of HP was 161 dB re 1 µPa^{2}s. The three pile-driving sounds were played back at 46 strikes/min.

Playback Equipment

The digitized sequences (WAV files; sample frequency 88.2 kHz, 16-bit) were played back in a loop by a laptop computer (ASUS Model P540U; ASUS Corporation, Taipei City, Taiwan) with a program written in *LabVIEW* to an external data acquisition card (National Instruments Model USB6251; National Instruments, Austin, TX, USA); the output was digitally controlled in 1 dB steps with the *LabVIEW* program. The attenuation system was linear over the SPL range used in the study. The output of the data acquisition card went via a ground loop isolator and a custom-built buffer to a power amplifier (East & West Model LS5002; E&W Corporation, Seoul, South Korea) that drove the transducer (Lubell Model 1424HP; Lubell Labs Inc., Columbus, OH, USA) through an isolation transformer (Lubell Model AC1424HP). The transducer was

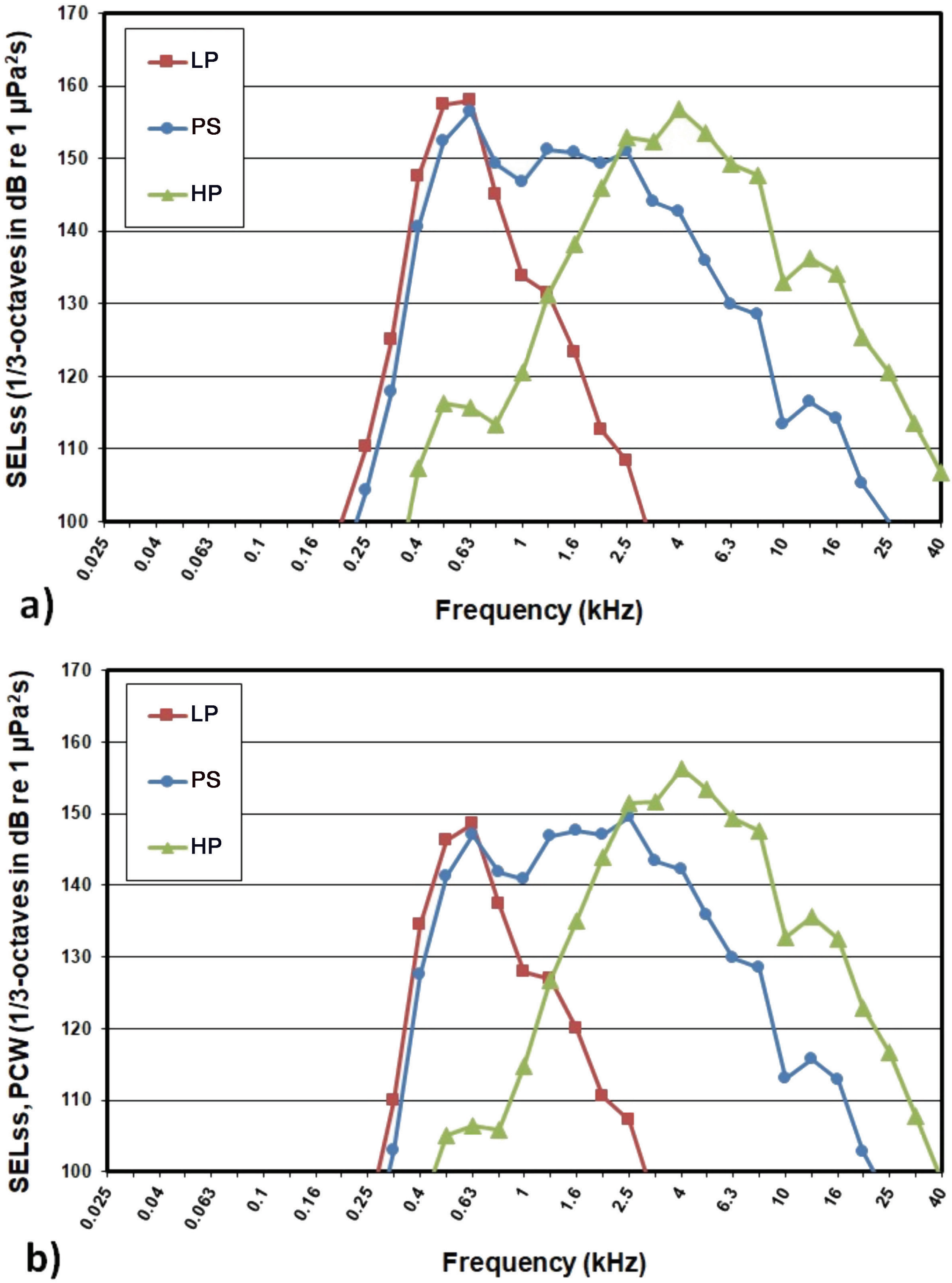


Figure 5. The measured one-third octave band spectra of the three pile-driving playback sounds used in Experiment 2: (a) the unweighted single-strike sound exposure level (SELss) and (b) the SELss as it is likely to be perceived by harbor seals, after application of the auditory weighting function for "phocid carnivores in water" (PCW; Southall et al., 2019, p. 134; Figure 1). The pile-driving playback sounds PS (minimally filtered), LP (low-pass filtered at 0.5 kHz), and HP (high-pass filtered at 4 kHz) were played back at an equal power-averaged unweighted SELss of 161 dB re 1 μPa²s. The spectra were measured at 1 m depth, 2 m from the transducer, and are linearly scaled to an unweighted SELss of 161 dB re 1 μPa²s.

placed at the northeastern side of the outdoor pool at 1.5 m depth (Figure 2).

Before each session, a 1.5-kHz frequency-modulated signal was used to monitor the output of the sound system to the transducer via a voltmeter (GW Instek Model EK202119 GMD-8251A; Goodwill Instruments Co., Taipei, Taiwan); the underwater sound was monitored with a custom-built hydrophone connected via a pre-amplifier (B&K Model 2635) and a spectrum analyzer (Velleman Model PCSU1000; Velleman, Gavere, Belgium) to a laptop computer (Lenovo Ideapad S130-11GM, Model 81J1; Lenovo, Beijing, China).

Acoustic Characterization of Pile-Driving Playback Sounds

The three pile-driving sounds were played back and then recorded in the pool. They were characterized in terms of the measured unweighted broadband SELss in dB re 1 μPa^2 over their duration (t_{90} in s): the time interval between the points when the cumulative sound exposure level (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 duration of individual pile-driving sounds increased due to reverberations in the pool, from 46 ms for the original recordings to 126 ms for the playback sounds.

Compared to the pile-driving playback sound PS, measured at 1 m depth, 2 m from the transducer, the pile-driving playback sound LP (Figure 5a) had less energy in the high-frequency part of the spectrum, and the pile-driving playback sound HP (Figure 5a) had less energy in the low-frequency part of the spectrum. The LP sound was narrower in its frequency band than PS and HP sounds. The one-third octave band spectrum of the sound exposure level with auditory weighting function for PCW (Southall et al., 2019; Figure 1), applied to each of the three pile-driving playback sounds, is shown in Figure 5b.

To determine the distribution of each pile-driving playback sound in the pool, the SELss was measured at spacings based on a horizontal grid of 1.2 m × 1.3 m, at three depths per location on the grid (0.5, 1.0, and 1.5 m below the surface). Figure 6 presents examples of the SELss distribution for the pile-driving playback sounds PS, LP, and HP at one source level: the highest mean SELss at which PS was produced in Experiment 1 (which was also the mean SELss at which the PS sound was produced in Experiment 2), and the mean SELss at which LP and HP were produced in Experiment 2 (mean unweighted broadband SELss 161 dB re 1 μPa^2s). No clear gradient existed in the SELss with distance from the transducer, resulting in a fairly homogeneous sound field (apart from the area within 1 m of the transducer, where the SELss were higher; Figure 6; mean for all three sounds: 161 dB re 1 μPa^2s [n = 99]; PS: SD = 2 dB, range 158 to 168 dB; LP: SD = 3 dB, range: 155 to 162; and HP: SD = 2.5 dB, range 156 to 168 dB). The harbor seals generally swam throughout the entire pool during the exposure periods, so the power-averaged SELss of all measurement locations was used to calculate the mean SELss to which they were exposed (Table 1).

Methodology

The transducer producing the pile-driving playback sounds was positioned in the water on the northeastern side of the pool at the start of each day (Figure 2). One session was conducted per day, up to 7 d/wk, beginning from 0830 h and ending by 1630 h. Each daily session consisted of either a 15-min baseline period (no sound emission; ambient noise only) or a 15-min test period (pile-driving sound emitted by playing back the PS, LP, or HP WAV file 138 times), followed by a pause of random length (no sound emission, no data collected for a minimum of 1 h, and continuing for at least 1 h after the seals had been fed to allow a rest period), followed by either a 15-min baseline or test period. The baseline and test periods were presented in random order, but each session included one baseline and one test period. During baseline and test periods, only the operator in the research cabin was allowed within 15 m of the pool, and she remained very still.

During each test period for Experiment 1 (dose-response relationship), the pile-driving playback sound PS was emitted at one of the seven SELss. Each level was tested in 15 test periods, resulting in 105 periods in all. The seven levels were tested in random order.

Experiment 2 (effect of weighting) was conducted similarly to Experiment 1, but each daily session consisted of either a 15-min baseline period (no sound emission; ambient noise only) or a 15-min test period (pile-driving sound emitted by playing back the PS, LP, or HP sounds for 15 min). The order of baseline and pile-driving playback sound was random. Each pile-driving sound was produced at the same broadband SELss in 30 test periods, resulting in 90 test periods in all. The three sounds were tested in random order.

At the beginning of each test period, the level of the pile-driving playback sound was slowly increased over a 1-min period to the desired SELss to prevent startle responses. To prevent masking of part of the spectrum by ambient noise, tests were not carried out during rainfall or when the ambient noise level was above that during Beaufort Sea State 4. Experiment 1 was conducted between September 2020 and April 2021. Experiment 2 was conducted between September 2021 and January 2022.

Behavioral Data Recording, Response Parameters, and Analysis

During baseline and test periods, the harbor seals' behavior was filmed by two cameras (Conrad Model 750940; Conrad Electronics, Berlin, Germany) with wide-angle lenses. Aerial camera 1 was placed on a pole 6 m above the water surface in the pool's southern corner (Figure 2). The entire surface of the pool was captured on the video image, except the areas below floating platform 1 and fixed inaccessible platform 3, which was 30 cm above the water. The output of this camera was digitized with an analog-to-digital converter (Zolid, Smart Group) and stored on a laptop (Medion Model MD98110). Aerial camera 2 captured the area below the inaccessible platform in the pool's eastern corner. During the experiment (and sometimes later from the video recordings), images from both cameras were viewed by the operator to evaluate where the harbor seals were swimming.

The spot-sampling method was used to record the behavior of the two harbor seals objectively. This was usually done live, with occasional checks from the video recordings. Each seal's behavior was recorded every 5 s, 180 times per 15-min baseline or test period. F02's head was marked with white zinc ointment at the beginning of each day (she was trained to voluntarily accept the application) so that the seals could be identified readily. Three behavioral parameters were used to quantify the seals' responses to the pile-driving playback sounds:

1. Position, classed as hauled out on a platform, at the water surface (body submerged; head out of the water), or fully underwater, expressed as a percentage of scores in each baseline and test period

a) PS pile-driving sound

0.5 m depth

	6	5	4	3	2	1
1	160	160	162	163	165	165
2	162	161	161	161	164	166
3	162	160	161	161		163
4	159	158	158	160	161	162
5	161	158	159	158	160	
6	159	160	159	160	161	

1.0 m depth

	6	5	4	3	2	1
1	158	159	161	163	164	164
2	162	160	161	162	163	166
3	161	159	160	159		163
4	160	159	159	159	161	161
5	161	159	159	159	159	
6	159	158	158	160	160	

1.5 m depth (depth transducer)

	6	5	4	3	2	1
1	158	160	162	163	164	164
2	162	161	161	162	164	168
3	161	160	160	160		163
4	160	159	159	160	159	160
5	161	160	160	159	160	
6	159	158	158	158	160	

b) LP pile-driving sound

0.5 m depth

	6	5	4	3	2	1
1	157	157	158	161	164	166
2	161	160	160	161	164	167
3	162	158	158	159		163
4	161	157	158	157	158	160
5	162	158	157	157	157	
6	158	156	155	157	156	

1.0 m depth

	6	5	4	3	2	1
1	158	159	161	163	166	166
2	162	161	162	164	166	168
3	163	160	161	161		162
4	162	158	159	160	160	161
5	163	159	159	160	159	
6	159	158	157	159	158	

1.5 m depth (depth transducer)

	6	5	4	3	2	1
1	156	157	160	162	164	163
2	160	159	161	163	164	169
3	161	158	160	160		159
4	159	156	157	158	159	158
5	160	156	158	158	158	
6	159	155	155	157	157	

c) HP pile-driving sound

0.5 m depth

	6	5	4	3	2	1
1	161	160	162	160	161	164
2	160	161	159	160	162	164
3	160	160	161	160		164
4	158	160	159	159	161	164
5	158	158	160	158	159	
6	159	158	158	163	162	

1.0 m depth

	6	5	4	3	2	1
1	159	159	160	161	162	164
2	158	158	161	160	163	165
3	158	158	161	160		164
4	157	158	159	160	159	165
5	157	158	159	159	161	
6	158	157	159	163	164	

1.5 m depth (depth transducer)

	6	5	4	3	2	1
1	159	159	162	163	164	164
2	158	159	162	164	166	168
3	159	159	160	162		167
4	157	158	160	160	161	167
5	158	156	161	160	161	
6	158	159	159	163	164	

Figure 6. The unweighted single-strike sound exposure level (SELss) distribution in the pool when pile-driving sounds were played back: (a) pile-driving playback sound PS (minimally filtered) at the maximum level in Experiment 1 (dose-response relationship) and the level used in Experiment 2 (effect of weighting); (b) low-frequency pile-driving playback sound (LP) at the level used in Experiment 2; and (c) high-frequency pile-driving playback sound (HP) at the level used in Experiment 2. The power mean SELss for all three sounds was 161 dB re 1 µPa²s ($n = 99$). Per location, the SELss did not vary systematically with depth. The grey blocks indicate the location of the floating haul-out platform 1 and the inaccessible area behind the barrier (the two grey boxes in the lower right-hand section; see Figure 2) where SELss measurements could not be made. The black dots indicate the location of the transducer at ~1.5 m depth. Measurements were made on a horizontal grid of 1.2 m × 1.3 m.

2. The distance (in m) between the harbor seals' locations and the transducer at scoring moments when the seals' heads were visible, during baseline and test periods (identified on a grid consisting of nine rectangles or on one of the two platforms; Figure 2)

3. The total number of times the harbor seals jumped out of the water during baseline and test periods (recorded continuously, not just every 5 s)

In Experiment 1, we presented the PS sounds at seven received levels and expected to see increasing responses with increasing SELss.

To investigate the harbor seals' responses to the pile-driving playback sounds, paired *t* tests were used to compare the percentage of time they spent at the water surface and their distance from the transducer in baseline and associated test periods; values for test minus baseline were compared to zero. Assumptions of the tests were conformed to, and the level of significance was 5% (Zar, 1999). Paired *t* tests on the same dependent variable for the same study animal were not considered to be independent, so *p* values were adjusted according to the Holm–Bonferroni method (Quinn & Keough, 2002). Since jumps out of the water were rarely observed, jumps in baseline and test periods were compared without formal statistical analysis; data on hauling out were compared in the same way. Examination of scatterplots of session number and behavioral parameters confirmed that the harbor seals did not habituate to the pile-driving playback sounds during the study.

Results

Experiment 1: Dose-Response Relationship

During baseline periods in Experiment 1, the harbor seals never hauled out on the platforms or jumped. They usually swam large ovals in the pool and spent on average 80% of their time fully underwater and 20% at the surface. Their distance from the transducer was on average 5.5 m.

During test periods, both harbor seals responded to pile-driving sounds by lifting their heads, partly or fully, out of the water. F01 increased the time she spent at the surface during test periods as the SELss increased, and she hauled out a few times when exposed to the highest SELss (Table 2; Figure 7). During test periods with two of the levels of the minimally filtered pile-driving playback sound PS, she moved away from the transducer. Though these movements were statistically significant, they were small (~0.5 m; Table 2). She jumped out of the water in test periods with high SELss (Table 2; Figure 7).

F02 did not spend more time at the surface during test periods than during baseline periods, and this did not change as the SELss increased; however, she did haul out more frequently during test periods as the SELss increased (Table 2; Figure 7). Her distance from the transducer was similar during baseline and test periods (Table 2). She jumped out of the water in test periods with high SELss (Table 2; Figure 7).

Considering the dose-response relationship as expressed by the harbor seals' positions and their jumps out of the water, the onset of behavioral response occurred at 131 dB re 1 $\mu Pa^2 s$ in F01 and at 137 dB re 1 $\mu Pa^2 s$ in F02. The response was very clear in both harbor seals from 143 dB re 1 $\mu Pa^2 s$.

Experiment 2: Effect of Weighting

F02 hauled out in 1% of scores in one of the 180 baseline periods in Experiment 2; otherwise, hauling out was only observed in test periods. During baseline periods, the harbor seals never jumped, usually swam large ovals in the pool, and spent on average 82% of their time fully underwater and 18% at the surface. Their distance from the transducer was on average 5.5 m.

During test periods, both harbor seals responded to all three pile-driving playback sounds by lifting their heads, partly or fully, out of the water (Table 3; Figure 8). F01 responded to the pile-driving playback sounds PS and LP by spending more time at the surface and by jumping; she also hauled out in response to playback sound PS. Her strongest response was to pile-driving playback sound HP: she moved away from the transducer, hauled out, and jumped out of the water (Table 3; Figure 8). F02 responded to all three sounds by increasing the time she spent at the surface, hauling out, and jumping out of the water (Table 3). Both seals responded strongly to PS and even more strongly to HP; in other words, they responded most to the sounds that they could hear best according to the weighting function (see Figure 1).

Discussion

Evaluation of the Study Animals and Results

The hearing sensitivity of the two harbor seals in the present study was similar (Kastelein et al., 2009a, 2009b), and their audiograms were representative of the hearing of harbor seals. However, the seals' responses to the pile-driving playback sounds may not have been representative, as we do not know the behavioral response repertoire of wild harbor seals. In addition, behavioral responses to sounds are context-dependent (Gomez et al., 2016). The context of the pool does not occur in the wild, though contexts in

Table 2. Comparison of behavioral data in test and baseline periods for each single strike sound exposure level (SELss) of the pile-driving playback sound PS (minimally filtered) in Experiment 1 (dose-response relationship) in harbor seals F01 and F02. The sample size for each comparison was 15. Paired *t* tests were used to compare percentage of scores at the water surface and distance from the transducer; *t* values and adjusted *p* values (Holm–Bonferroni method; Quinn & Keough, 2002) are shown. NS = not significant; SD = standard deviation. In all cases where the test was significant, the mean value for the test period was greater than that for the baseline period. The harbor seals did not haul out or jump during baseline periods; all hauling out observed and the total number of jumps recorded during all test periods are shown.

Harbor seal	SELss of pile-driving playback sound PS in test periods (dB re 1 µPa²s)	% of scores at water surface (test minus baseline)	% of scores hauled out during the 15 test periods	Distance from transducer (m; test minus baseline)	No. of jumps in all 15 test periods combined
F01	125	T = 1.12, $p = 0.283$ NS	None	T = 2.83, $p = 0.065$ NS	0
	131	T = 3.03, $p = 0.018$	None	T = 3.83, $p = 0.014$ (displacement: 0.55 ± 0.56 m – mean ± SD)	0
	137	T = 4.04, $p = 0.003$	None	T = 3.68, $p = 0.012$ (displacement: 0.46 ± 0.49 m – mean ± SD)	0
	143	T = 4.73, $p = 0.000$	None	T = 1.55, $p = 0.288$ NS	2 in 2 test periods
	149	T = 6.76, $p = 0.000$	1% in 1 test period	T = 2.68, $p = 0.072$ NS	9 in 4 test periods
	155	T = 9.12, $p = 0.000$	None	T = 2.18, $p = 0.141$ NS	22 in 9 test periods
	161	T = 10.71, $p = 0.000$	3 and 24% in 2 test periods	T = 0.53, $p = 0.606$ NS	29 in 12 test periods
F02	125	T = 1.61, $p = 0.520$ NS	None	T = -0.99, $p = 1.000$ NS	0
	131	T = 0.95, $p = 1.000$ NS	None	T = 0.77, $p = 1.000$ NS	0
	137	T = 0.02, $p = 0.984$ NS	1, 3, and 4% in 3 test periods	T = 1.06, $p = 1.000$ NS	1
	143	T = 0.25, $p = 1.000$ NS	2 to 9% in 6 test periods	T = 2.04, $p = 0.427$ NS	3 in 2 test periods
	149	T = 4.11, $p = 0.007$	1 to 4% in 4 test periods	T = 1.18, $p = 1.000$ NS	4 in 3 test periods
	155	T = 2.30, $p = 0.190$ NS	2 to 43% in 9 test periods	T = -0.07, $p = 0.947$ NS	2 in 2 test periods
	161	T = 2.88, $p = 0.072$ NS	3 to 38% in 12 test periods	T = -0.49, $p = 1.000$ NS	11 in 7 test periods

the wild are innumerable. Conducting the behavioral response experiments in a pool had advantages: the ambient noise could be kept very low, the pile-driving sound levels could be controlled accurately, the seals' behavior could be filmed, and the context could be kept as consistent as possible. The two seals rarely swam together and never jumped together, and their responses to the sounds differed (Figures 7 & 8). However, they were together in the pool and so their behavior cannot be considered independent.

The behavioral parameter "distance from the transducer" in the present study was probably not very useful. Unlike in an avoidance study with harbor seals in a larger pool that had a SELss gradient (e.g., Kastelein et al., 2006), the SELss distribution in the pool in the present study was fairly homogenous (Figure 6); there were no underwater locations with very low SELss where the seals could go to reduce their sound exposure. However, the behavioral parameters "position" and "jumps" were informative. When exposed to high-amplitude sound from a seal acoustic harassment device in nature, some harbor seals raised their heads above the water surface (Mate et al., 1987).

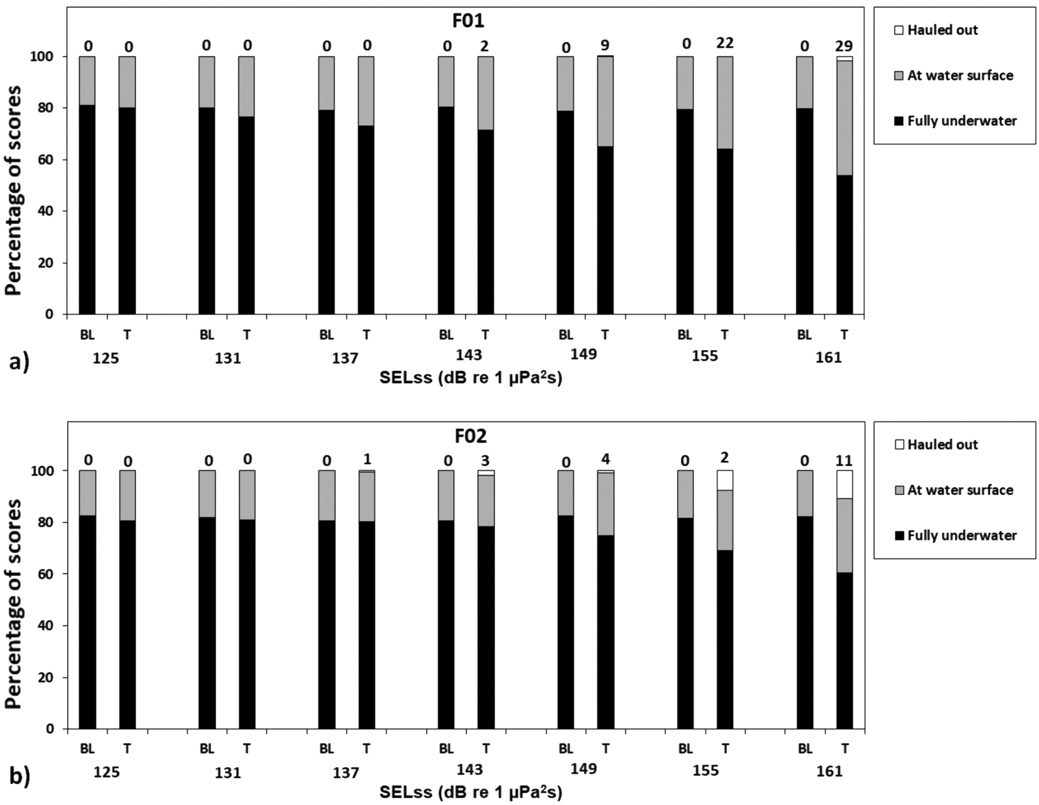


Figure 7. The percentage of scores spent hauled out, at the water surface, and fully underwater in Experiment 1 (dose-response relationship) by harbor seals F01 (a) and F02 (b) during baseline periods with ambient noise (BL) and during test periods (T) with exposure to pile-driving playback sound PS (minimally filtered); $n = 15$ for each column. The pile-driving sound was played back at seven unweighted SELss (125 to 161 dB re 1 µPa²s). The number above each column is the total number of jumps in the 15 test or baseline periods (no jumps occurred during the baseline periods). The seals' behavior during baseline periods was similar and consistent. During test periods, both seals responded more strongly as SELss increased.

The effects in the present study occurred under very low ambient noise conditions (lower than those observed during Beaufort Sea State 0). Under higher ambient noise conditions, responses would be expected to be less strong (due to masking, changes in the impulsiveness of sounds, and changes in spectrum due to filtering by seawater, such as high-frequency absorption and reverberation). A study of behavioral responses of harbor porpoises (*Phocoena phocoena*) to sonar sounds of equal SPL under different ambient noise conditions showed that the response to the sonar sounds decreased as ambient noise increased (Kastelein et al., 2011).

Dose-Response Relationship

As the unweighted broadband SELss of the pile-driving sounds increased in Experiment 1, both harbor seals reduced their sound exposure, mainly by removing their ears from the water. Considering the dose-response relationship as expressed by the seals' position and their jumps out of the water, the onset of behavioral response occurred at 131 dB re 1 µPa²s in F01 and at 137 dB re 1 µPa²s in F02. The response was very clear in both seals from 143 dB re 1 µPa²s.

Harbor seals in nature also react to pile-driving sounds. Russell et al. (2016) tracked harbor seals during construction of a wind farm and found no significant displacement during construction as a whole. However, during pile-driving, seal abundance was significantly reduced up to 25 km from the pile-driving site, compared to during breaks in pile driving. Significant displacement occurred at predicted peak-to-peak received SPLs of 166 to 178 dB re 1 µPa. Within 2 h of cessation of pile driving, harbor seal abundance returned to normal (Russell et al., 2016). In Experiment 1 of the present study, unweighted SELss of 140 dB

Table 3. Comparison of behavioral data in test and baseline periods for each pile-driving playback sound in Experiment 2 (effect of weighting) in harbor seals F01 and F02. The sample size for each comparison is 30 unless indicated otherwise (distance from the transducer could not be calculated when 100% of scores in a test period were spent hauled out). Paired *t* tests were used to compare percentage of scores at the water surface and distance from the transducer; *t* values and adjusted *p* values (Holm–Bonferroni method; Quinn & Keough, 2002) are shown; NS = not significant. Where the test was significant, the mean value for the test period was greater than that for the baseline period, with one exception: F01 spent significantly less time at the water surface during test periods with the high-frequency pile-driving playback sound (HP) than during baseline periods (indicated with †). The seals did not haul out or jump during baseline periods; all hauling out observed and the total number of jumps recorded during all test periods are shown.

Harbor seal	Pile-driving playback sound	% of scores at water surface (test minus baseline)	% of scores hauled out during the 30 test periods	Distance from transducer (m; test minus baseline)	No. of jumps in all 30 test periods combined
F01	LP (low-frequency)	T = 9.74, $p = 0.000$	0.5% in 1 test period	T = 1.08, $p = 0.582$ NS	9 in 7 test periods
	PS (minimally filtered)	T = 3.66, $p = 0.001$	0.5 to 100% in 19 test periods	T = 1.02, $p = 0.318$ ($n = 25$) NS	56 in 17 test periods
	HP (high-frequency)	T = -8.37, $p = 0.000$†	24 to100% in all 30 test periods	T = 5.53, $p = 0.000$ ($n = 24$) (displacement: 0.8 ± 0.7 m – mean ± SD)	84 in 18 test periods
F02	LP (low-frequency)	T = 6.31, $p = 0.000$	2 to 24% in 13 test periods	T = -0.18, $p = 1.000$ NS	4 in 3 test periods
	PS (minimally filtered)	T = 5.81, $p = 0.000$	1 to 65% in 17 test periods	T = -0.19, $p = 1.000$ NS	15 in 7 test periods
	HP (high-frequency)	T = 5.53, $p = 0.000$	1 to 97% in 20 test periods	T = -0.07, $p = 0.948$ NS	17 in 9 test periods

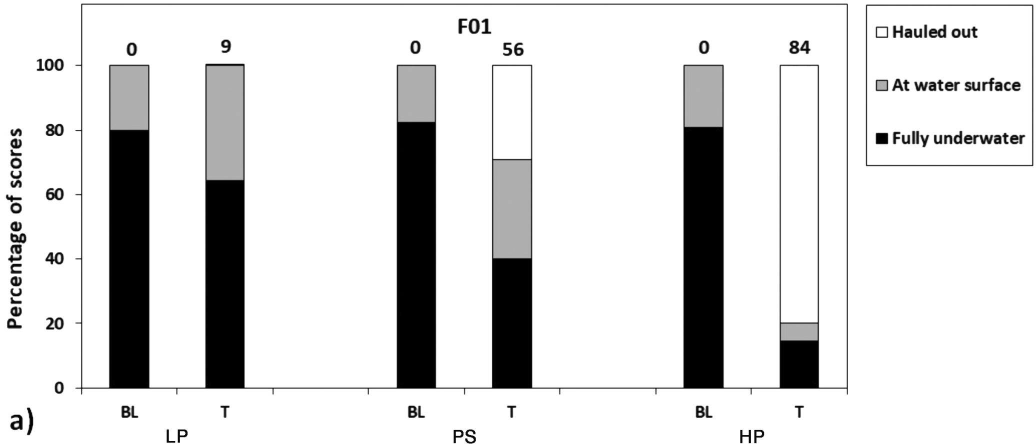
corresponds to peak-to-peak SPLs of ~170 to 172 dB, within the range in which Russell et al. (2016) saw effects in harbor seals at sea.

Effect of Weighting: Behavioral Responses, Exposure Criteria, and Mitigation

In Experiment 2, the SELss of the pile-driving playback sounds were well above the threshold for the onset of behavioral responses suggested by Experiment 1, and, as expected, both harbor seals responded to all three sounds. The different responses to the three sounds with similar unweighted SELss, and the fact that the strongest response was to pile-driving playback sound HP and the weakest response was to pile-driving playback sound LP, suggest that frequency weighting is likely to improve the prediction or explanation of responses to sounds by harbor seals. Auditory frequency weighting is also likely to be important when determining the dose in formal models of dose-response relationships for disturbance of seals by sound. However, as the playback sounds used in the present study did not capture the full frequency spectrum of offshore piling sounds, the extent to which the seals' response to the weighted SELss in this study can be extrapolated to realistic offshore piling scenarios remains unclear.

Frequency weighting is also likely to improve predictions of behavioral responses of harbor porpoises to sounds. A captive harbor porpoise changed its respiration rate when presented with pile-driving sounds at unweighted SELss of ≥ 127 dB re 1 µPa^{2}s and jumped out of the water more often in response to higher levels (Kastelein et al., 2013a). In a study similar to the present one, but in a larger pool with an SELss gradient, a harbor porpoise was presented with pile-driving sounds, some of which were filtered to remove the high-frequency components. In response to pile-driving sounds with high-frequency components, the porpoise increased her respiration rate, swam faster, and jumped out of the water more often than she did in response to the sounds that were predominantly low frequency (Kastelein et al., 2022). She moved away from the transducer in response to all pile-driving sounds. Therefore, the porpoise was able to hear all the sounds, but she changed some of her behaviors only in response to the higher-frequency pile-driving sounds (Kastelein et al., 2022).

The present study and the study with harbor porpoises (Kastelein et al., 2022) show that the high-frequency components of pile-driving sounds are more disturbing to these marine mammals than the low-frequency components (though the very



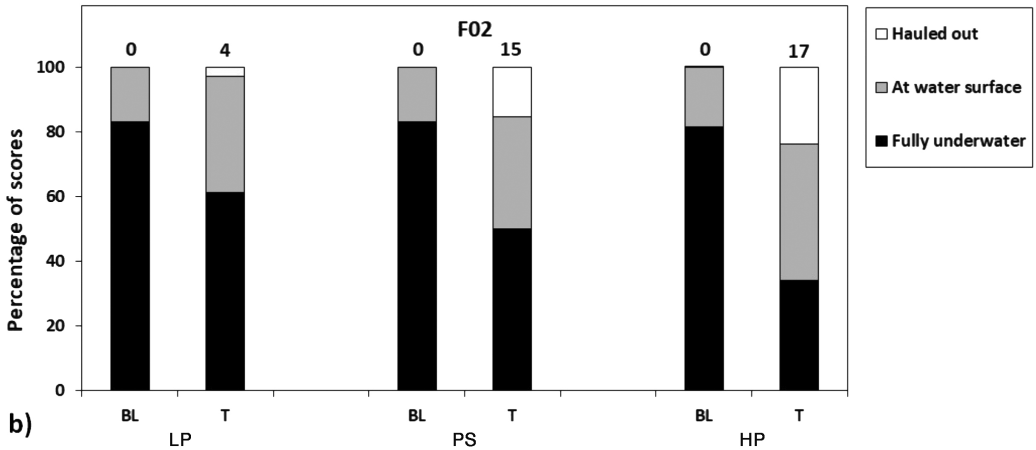


Figure 8. The percentage of scores spent hauled out, at the water surface, and fully underwater in Experiment 2 (effect of weighting) by harbor seals F01 (a) and F02 (b) during baseline periods with ambient noise (BL) and during test periods (T) with exposure to the pile-driving playback sounds PS (minimally filtered), LP (low-pass filtered at 0.5 kHz), and HP (high-pass filtered at 4 kHz); n = 30 for each column. The pile-driving sounds were played back at the same unweighted SELss (161 dB re 1 µPa^{2}s) but with increasing weighted SELss (LP: 151 dB, PS: 156 dB, HP: 161 dB). The numbers above the columns are the total number of jumps in the 30 baseline or test periods (no jumps occurred during the baseline periods). The seals' behavior during all baseline periods was similar and consistent. During test periods, both seals responded to all three pile-driving playback sounds, and both responded more strongly to the pile-driving playback sounds PS and HP than to the LP playback sounds.

low-frequency elements of pile-driving sounds in these studies were filtered out to some extent). The low-frequency hearing of harbor seals is relatively poor (Kastelein et al., 2009a, 2009b), and that of harbor porpoises is even worse (Kastelein et al., 2017a). Applying the auditory weighting functions for seals and porpoises to broadband sounds means that the high-frequency parts of the spectrum that elicit strong responses are emphasized (Southall et al., 2019), thus improving predictions of their effects on harbor seals and harbor porpoises. Similar principles may apply to other marine mammal species, suggesting that applying species-specific (or group-specific) frequency-weighted auditory functions to sounds can improve both predictions of responses and the definition of safety criteria.

Auditory frequency weighting can also inform the development of mitigation measures. The present study and the similar study with harbor porpoises (Kastelein et al., 2022) show that removing the high-frequency components of broadband pile-driving sounds can reduce their effect on the behavior of these marine mammals. It is easier to remove the short-wavelength high-frequency sounds using bubble screens and cofferdams than it is to remove the low-frequency part of the spectrum (Dähne et al., 2017). Such mitigation measures (i.e., the removal of the high-frequency part of the spectrum) are likely to benefit both harbor seals and harbor porpoises.

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