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Hearing thresholds of two harbor seals (*Phoca vitulina*) for playbacks of multiple pile driving strike sounds

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Abstract

Pile driving, which creates high amplitude sounds with potentially negative impacts on the marine environment, is used to attach wind turbines to the sea bed. To quantify the distance at which pile driving sounds can be detected by harbor seals, unmasked hearing thresholds were obtained for series of five pile driving sounds recorded at 100 and 800 m from a pile driving location. The played back spectra resembled the spectra of sounds recorded under certain conditions 10-50 km from an offshore pile driving site. The lower the received level, the later within the series of sounds the harbor seals responded. The mean 50% detection threshold sound exposure levels (SELs) for any sound in the series were: 40 (seal 01, 100 m), 39 (seal 01, 800 m), 43 (seal 02, 100 m), and 43 (seal 02, 800 m) dB re 1 $\mu Pa^2 s$ (add 9 dB for SPLs, dB re 1 μPa). The mean 50% detection thresholds based on detection of only the first sound of the series were ca. 5 dB higher. Detection at sea depends on the actual propagation conditions and on the degree of masking of the sounds by ambient noise, but the present study suggests that pile driving sounds are audible to harbor seals up to hundreds of kilometers from pile driving sites.

I. INTRODUCTION

For the sustainable development of the offshore renewable energy industry, it is necessary to reduce or avoid the damaging effects of noise, from activities such as pile driving to attach wind turbines to the sea bed, on marine mammals. Sound is particularly important for marine mammals, as it may be used as a means of orientation, communication, and to locate prey, conspecifics and predators (Richardson *et al.*, 1995). Therefore, marine animals are likely to be disturbed by noise in their environment, and noise at sea may have negative physiological, auditory, and/or behavioral effects on them. The harbor seal (*Phoca vitulina*) may be negatively influenced by pile driving sounds, as it is exposed to them relatively often in its large distribution area in the coastal waters of the Northern Hemisphere. Coastal waters are suitable for wind farms, because turbines are easy to build in shallow water, and because the loss of electrical power is low, due to the proximity of generators to the end users.

As a first step in assessing the impact of pile driving sounds on harbor seals, it is important to determine their hearing thresholds for these sounds. Hearing thresholds are required, in combination with source levels and ambient noise levels, to calculate the extent of audibility zones. So far, the underwater hearing of harbor seals has been quantified for pure tones (Møhl, 1968; Terhune, 1988; Turnbull and Terhune, 1990; Kastak and Schusterman, 1998; Southall *et al*., 2005; Kastelein *et al*., 2010b), narrow-band frequency-modulated (FM) signals (Kastelein *et al*., 2009a), and 1/3-octave noise bands (Kastelein *et al*., 2009b). Despite their differences, these sounds are all relatively simple and have relatively narrow frequency bands. It is unknown what the hearing threshold of harbor seals is for broadband sounds of short duration (i.e., below the integration time of harbor seal hearing), such as those produced by pile driving.

As the distance between a pile driving site and an animal increases, the spectra and duration of the pile driving sounds change due to differential absorption and reflections. Therefore, the detection of pile driving sounds at a given distance depends not only on the received level, but also on the propagation characteristics.

The aim of the present study was to determine the unmasked hearing threshold of two harbor seals for playbacks of series of pile driving sounds recorded at two distances from a pile driving site.

II. MATERIALS AND METHODS

A. Study animals

The two female harbor seals (ID numbers 01 and 02) used in this study were four years old and each weighed approximately 50 kg. The seals had participated in three similar psychophysical hearing studies (Kastelein *et al*., 2009a, b; 2010b), and so were well accustomed to the daily hearing test routine. The animals received around 2 kg of thawed fish per day, equally divided over three meals. Variation in the animals' hearing test performance was minimized by making weekly adjustments (usually in the order of 100 g) to their daily food ration, based on their weight and performance during the previous week, and the expected change in water and air temperatures in the following week.

B. Study area

The study was conducted at the SEAMARCO Research Institute (Goes, The Netherlands), which is in a remote area specifically selected for acoustic research, in an outdoor pool (8 x 7 m, 2 m deep) with an adjacent haul-out platform. The pool was constructed to be as quiet as possible and to reduce reflections of sounds above 25 kHz (see Kastelein *et al.*, 2009a).

During test sessions, the harbor seals were tested in random order. The seal being tested positioned itself with its muzzle touching the end of the listening station (an L-shaped, 32 mm-diameter, water-filled polyvinylchloride tube with an end cap). To allow the animal's position at the listening station to be checked, she was filmed from above by means of an underwater video camera which was attached to the listening station. The images were visible to the operator in the research cabin. The animal not being tested was trained to keep very still and quiet for 15 minutes in the water next to the haul-out platform or on the platform. The operator and the equipment used to produce the sounds were in a research cabin next to the pool, out of sight of both animals.

C. Background noise and stimuli level calibration measurements

Great care was taken to make the harbor seals' listening environment as quiet as possible. Nobody was allowed to move within 15 m of the pool during sessions. Underwater background noise levels were measured under the same weather conditions as during the test sessions (no rain, and wind speed corresponding to Beaufort 4 or below). The background noise in the pool was very low (see Kastelein *et al.*, 2010b).

Prior to the actual tests, the received sound exposure level (SEL in dB re 1 $\mu Pa^2 s$) of the played back pile driving sounds was measured, in the absence of the seals, by using two hydrophones, one at the location of each auditory meatus of the seal when it was positioned at the listening station. The SELs at the two locations differed by 0-2 dB. The average SEL from the two hydrophones was used to calculate the detection thresholds. During trials, the seal's head position (at the listening station) was carefully monitored, and was consistent to within 2 cm for each external auditory meatus (a maximum of 2 degrees off the beam axis of the transducer). The received SELs were calibrated up to levels of around 50 dB above the threshold levels found in the present study. The linearity of the transmitter system was checked several times during the study; it was consistent to within 1 dB over the 20 dB attenuation range used in this study. The recording equipment is described in detail by Kastelein *et al.* (2010b).

D. Test stimuli

The stimuli were playbacks of two series of offshore pile driving sounds, one recorded at 100 m and one at 800 m from a pile being driven into the sea bed as the foundation for a wind turbine for the Dutch offshore wind farm 'Egmond aan Zee' in the North Sea. WAV files were made of series of five consecutive pile driving strike sounds**.** Sounds were recorded at two distances in order to evaluate the effect of recording distance on the spectra (**Figs. 1a and 2a; Table I**). Although recordings from a wider range of distances would have been preferable, at the time of the study these were the only recordings available. 90% of the energy in the individual sounds was contained in the 63 Hz to 400 Hz frequency region. The recordings were sampled at 88.2 kHz and high-pass filtered at 50 Hz, to avoid overloading the projector with low frequency sounds outside its operational frequency range.

The digitized original recordings of the pile driving sounds (WAV files) were played back on a laptop computer (Acer Aspire - 5020) using Adobe Audition (version 3.0). The output of the laptop passed through a FireWire interface (LogiLink - 1394A), an external sound card (Presonus - Inspire 1394), and a ground loop isolator, to a modified audiometer for testing human aerial hearing (Madsen Electronics, Midimate, model 622 with extended frequency range) that controlled the sounds' amplitude. The playback level could be varied in 2 dB increments. The played back pile driving sounds were emitted through an isolation transformer (Lubell – AC202) and projected underwater via a balanced tonpilz piezoelectric acoustic transducer (Lubell - LL 916). Details of the transducer and listening station are given by Kastelein *et al.* (2010b).

The SEL of the played back sounds (based on a single strike sound) was measured in the pool (**Figs. 1b and 2b**). The 1/3-octave band spectrum of the SEL (over the 90% energy duration of the sound) of the played back sounds, recorded at the listening position of the harbor seals, is shown in **Fig. 3**.

The five individual pile driving sounds played back in the pool in the series differed slightly from one another. The mean (± SD) of the acoustic parameters (at the maximum output level) for the five sounds are given in **Table I**. The differences between the 100 m and 800 m recordings at sea, and the differences between the 100 m and 800 m played back sounds, were minor. The original recordings and played back sounds differed in spectrum (**Fig. 3**), signal duration and zero-peak pressure, but they also had some characteristic features in common. The duration of both original recordings and played back sounds was less than the integration time of the harbor seal's hearing system for signals in the frequency range between 200 Hz and 2 kHz (>360 ms; Kastelein *et al.*, 2010). 90% of the energy in the played back sounds was contained in the 800 Hz to 2 kHz frequency region. Below 200 Hz, the original recordings could not be reproduced efficiently due to the characteristics of the projector and the shallow water in the pool. Above 5 kHz, recording the played back sounds in the pool was hampered by electronic noise in the measurement system. To eliminate electronic noise, a digital filter (3rd order Butterworth low-pass at 5 kHz) was applied to the sounds. This filter did not influence the reported broadband detection threshold level significantly, because the energy was predominantly contained in the 0.8 to 2 kHz frequency range. The spectra of the played back pile driving sounds in the pool resembled those of pile driving sounds recorded on one specific occasion 10-50 km from an offshore pile driving site in the North Sea (such sounds may vary depending on the piling and environmental conditions).

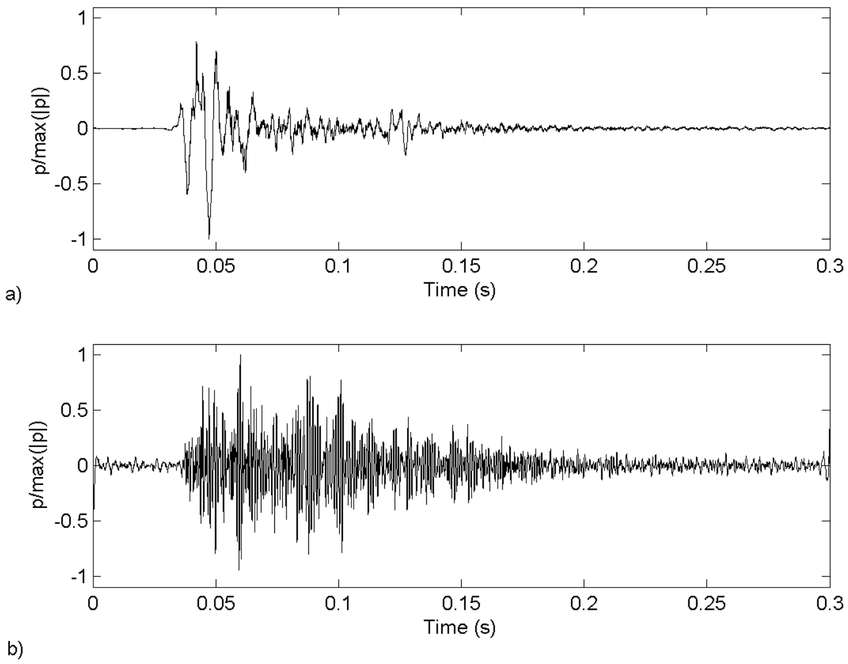

FIG. 1. Waveform of a single pile driving sound recorded at 100 m from the pile driving site (a), and of the played back sound in the pool (b). The amplitude of the sound pressure is scaled to the maximum absolute value of instantaneous sound pressure.

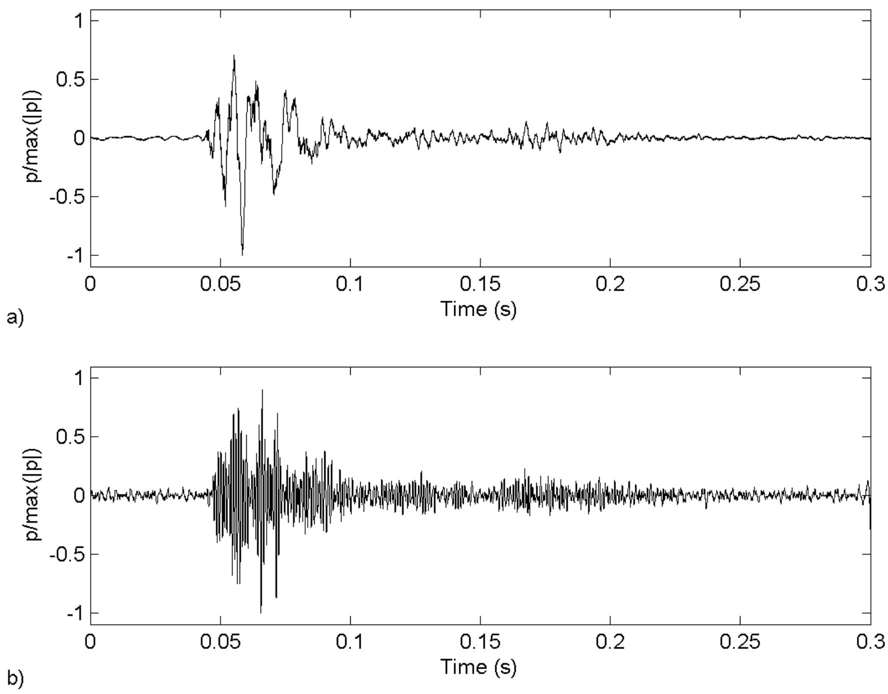

FIG. 2. Waveform of a single pile driving sound recorded at 800 m from the pile driving site (a), and of the played back sound in the pool (b). The amplitude of the sound pressure is scaled to the maximum absolute value of instantaneous sound pressure.

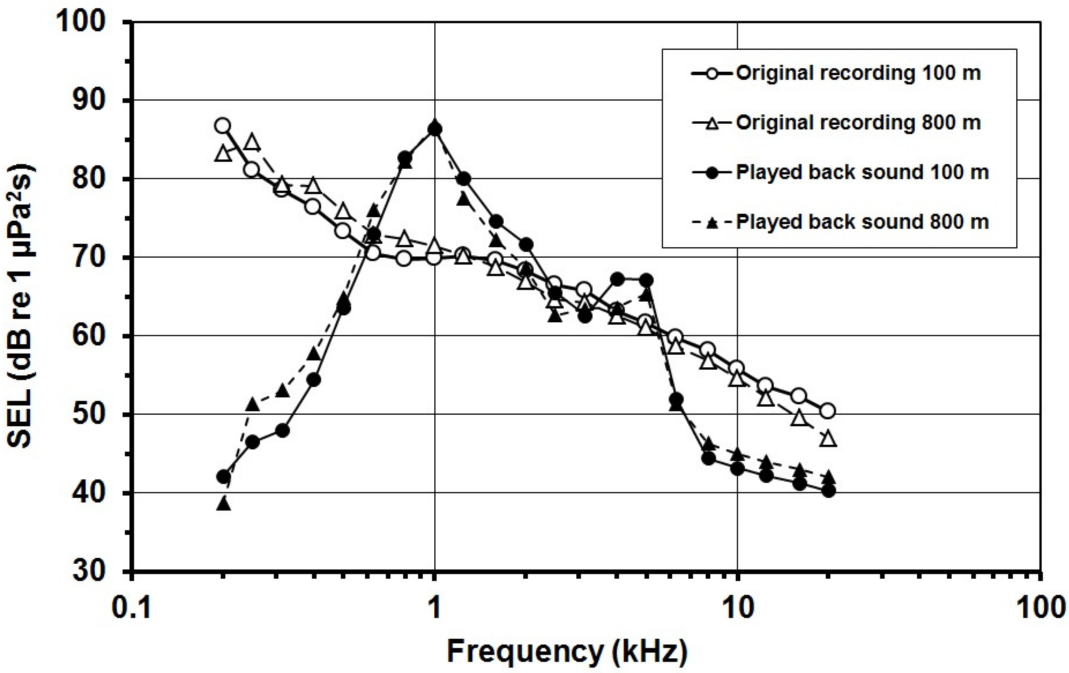

FIG. 3. The 1/3-octave band spectra of the SEL (over the 90% energy duration of a single strike sound) of the original and the played back pile driving sounds in the pool. All spectra are scaled to the same total unweighted broadband SEL of 89 dB re 1 $\mu Pa^2 s$ in the 200 Hz to 20 kHz 1/3-octave bands.

Table I. Properties of the original recordings of pile driving sounds and of the played back sounds (at a particular level) as recorded in the pool. t_{90} is the 90% energy duration of the sound, $p_{z\text{-}p}$ the maximum absolute value of the instantaneous sound pressure, and SEL the single sound exposure level. Values are shown as means ± SD (standard deviations) for the five pile driving strike sounds.

Sound	Hammer energy (kJ)	Rate (strikes/min)	Interpulse interval (s)	t_{90} (ms)	Peak pressure $p_{z\text{-}p}$ (Pa)	Peak SPL $L_{z\text{-}p}$ (dB re 1 μPa)	SEL (dB re 1 μPa^2s)
Original (100 m)	380	51	1.2	47 (± 17)	10000 (± 1000)	200	177 (± 1)
Original (800 m)	690	46	1.3	46 (± 8)	5000 (± 500)	194	171 (± 1)
Played back (100 m)	-	51	1.2	115 (± 5)	112 (± 2)	161	89 (± 2)
Played back (800 m)	-	46	1.3	128 (± 10)	111 (± 1)	161	87 (± 1)

E. Experimental procedure

A psychophysical method was used to determine the harbor seals' hearing thresholds (for details, see Kastelein *et al.* 2010b). A trial began when the seal not being tested was near the platform with a trainer, and the seal being tested was positioned with its head at the start/response buoy at the edge of the pool, next to the test animal's trainer. At a signal from the trainer, the seal swam to the listening station.

Two trial types were conducted during each experimental session: signal-present trials and signal-absent trials. In signal-present trials, the first sound of the series of five was presented unpredictably, between 4 and 14 s (established via a random number generator) after the animal stationed at the listening station. We chose a relatively long waiting period to prevent the animals becoming 'trigger happy', which was possible because we used only 1/3 of the trials as control trials, and 2/3 as signal trials to increase threshold data collection. The longer the waiting period, the smaller the chance of labeling an animal's false response as a signal detection. If the animal detected a sound, it was trained to leave the station ("go" response) at any time during the transmission of the sound or within 200 ms after it, and return to the start/response buoy. Reaction times of these seals performing this psychophysical task are in the order of a few hundred ms (Kastelein *et al.*, 2011). The signal duration was around 120 ms and the interpulse interval was around 1250 ms. Each time a sound in the series was produced, a generator was activated that produced horizontal white lines on the video image. This helped the operator to determine visually which sound in the series the seal responded to. If the animal responded to any one of the five sounds in a series, the signal operator told the trainer that the response was correct, after which the trainer gave the seal a fish reward. The operator recorded the sound (strike) number (1-5) to which the seal responded. If the animal did not respond to any of the five pile driving sounds in the series ("no-go" response), the signal operator signaled this to the trainer. The trainer then signaled to the animal (by tapping three times on the side of the pool) that the trial had ended, thus calling her back to the start/response buoy. No reward was given.

A session generally consisted of 30 trials per animal (one trial being a test of a series of five pile driving sounds) and lasted for about 15 minutes per animal. The order in which the seals were tested was random. Sessions consisted of ~70% signal-present and ~30% signal-absent trials, presented in quasi-random order; there were never more than three consecutive signal-present or signal-absent trials. In order to end with a positive event, the last trial for each seal was always one in which she responded correctly and received a reward. For each session, and for each seal, one of four data collection sheets was used. Each sheet comprised a different randomly ordered set of signal-present and signal-absent trials, and a list of random times to be applied between the animal stationing and sound presentation. In each session, series of pile driving sounds recorded at only one distance (100 or 800 m) were tested with both seals, but the amplitude was varied according to the 1-up 1-down adaptive staircase method (2 dB steps). This conventional psychometric technique (Robinson and Watson, 1973) results in a 50% correct detection threshold (Levitt, 1971).

Thresholds were determined for series of sounds recorded at each distance. To prevent the animals' learning process from affecting the threshold levels, the sounds recorded at the two distances were tested in random order. Usually two experimental sessions per day with each animal were conducted, five days per week (at 0900 and 1300 h) between July and August 2010.

F. Determination of detection thresholds

Switches in the harbor seals' response, from detecting any one sound in the series of five (a hit), to not detecting any of the five sounds (a miss), or *vice versa*, called reversals, were used to calculate detection thresholds. A detected level and the successive undetected level, or *vice versa,* are called a reversal pair. Detection thresholds were calculated for each harbor seal and for sounds recorded at each distance, for any of the five pile driving sounds in each series (seals sometimes did not respond to the first sound in the series, but did respond to sound number 2, 3, 4 or 5). Each series of played back pile driving sounds was tested until at least 104 reversal pairs had been obtained (in 12 or 13 sessions). Differences in 50% detection thresholds (SEL, any of the five sounds in the series) due to the distance at which the original recording was made at sea (100 and 800 m) and due to the individual seal were examined by means of analysis of variance (ANOVA; Zar, 1999). The 50% detection thresholds were also calculated for only the first sound of the series, disregarding any response to sound numbers 2, 3, 4 and 5, by taking the mean of all the lowest levels of the first strike an animal responded to, and subtracting 1 dB, as 2 dB steps were used.

Hearing thresholds are usually expressed as Sound Pressure Levels (SPLs). However, the SPL is dependent on the averaging time chosen for the squared pressures, and it is not clear what time window should be chosen for impulsive sounds (Madsen, 2005). The Sound Exposure Level (SEL: 10 times the 10 base log of the time integral [seconds] of the squared pressure over a time window including the complete impulsive sound, in dB re 1 $\mu Pa^2 s$) is independent of the length of the time window. The SEL is used here to characterize the 50% detection threshold for sounds that are shorter than the integration time of the hearing system.

III. RESULTS

The pre-stimulus response rates of harbor seal 01 varied between 3 and 5% depending on the pile driving sound; those of seal 02 varied between 2 and 3% (**Table I**). Rates fell within the ranges found in previous psychoacoustic hearing studies with these animals.

There was a significant (~3 dB) difference between the two harbor seals for the 50% detection threshold based on any of the five sounds (**Fig. 4, Tables II and III**). The two seals responded in different ways to the sounds recorded at different distances. Seal 01's threshold was 1 dB lower for sounds recorded at 800 m than for those recorded at 100 m, whereas the detection thresholds of seal 02 for the sounds recorded at the two distances were similar (ANOVA, **Table III**). The mean 50% hearing thresholds based on detection of only the first sound were approximately 5 dB higher than those based on detection of any one of the five sounds (**Table II**).

Table II. The pre-stimulus response rates (for both signal-present and signal-absent trials), and mean 50% detection threshold levels expressed in SEL (± S.D.), based on any sound in the series of five, and based on only the first sound of the series, of the two 4-year-old female harbor seals for the played back pile driving sounds (recorded at 100 and 800 m from the pile driving location). The values between brackets are mean SPLs (dB re 1 re 1 µPa).

	Seal 01		Seal 02	
	Pile driving sound recorded at:		Pile driving sound recorded at:	
	100 m	800 m	100 m	800 m
Signal duration (t90 in ms)	115	128	115	128
Pre-stimulus response rate	5%	3%	3%	2%
Mean 50% detection threshold for any one of five sounds SEL (dB re 1 μPa^2 s)	40 ± 2 (49)	39 ± 2 (48)	43 ± 2 (52)	43 ± 2 (52)
Mean 50% detection threshold first sound SEL (dB re 1 μPa^2 s)	44± 2 (53)	45± 2 (54)	48 ± 2 (57)	48 ± 2 (57)

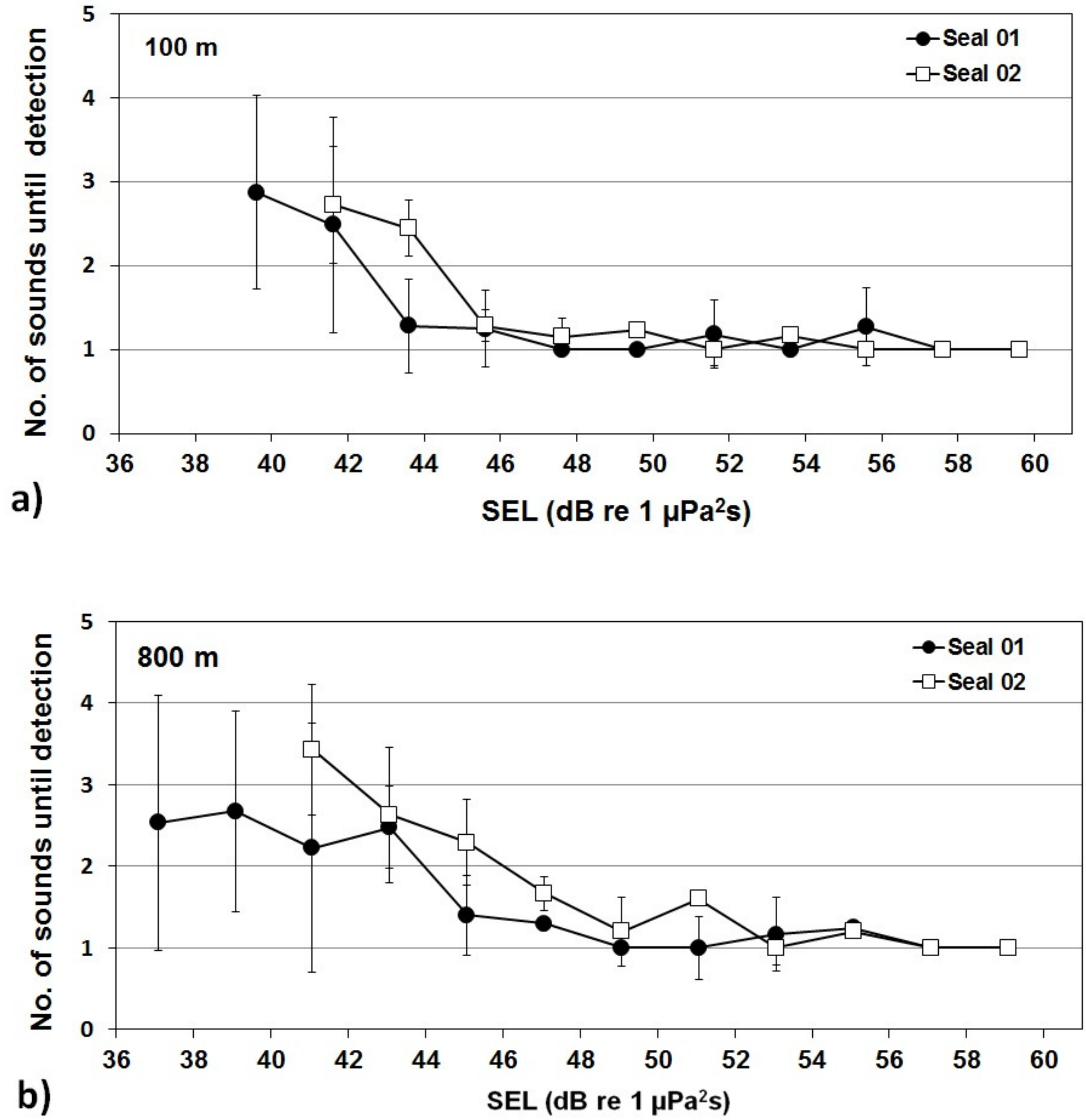

FIG. 4. The received broadband sound exposure level (SEL based on a single pulse) in relation to the mean pile driving sound number (of series of five sounds) which the two harbor seals detected (the bars indicate ± the standard deviation, sample sizes vary between 2 and 41 due to the up-down hearing test method used); a) for sounds recorded at 100 m from the pile driving location, and b) for sounds recorded at 800 m. For SPL (dB re 1 μPa), add 9 dB to the SEL values.

Table III. ANOVA on 50% detection thresholds (SEL; for any of the five pile driving sounds in the series), showing significant variation due to individual harbor seal and due to the interaction between seal and recording distance (100 or 800 m from the site of pile driving). Seal 01 had a lower threshold (more sensitive hearing) than seal 02, and seal 01's threshold was lower for sounds recorded at 800 m than for those recorded at 100 m.

Source of variation	**DF**	**Adjusted mean square**	**F**	***P***
Distance	1	1.206	0.60	0.442
Seal	1	130.006	64.74	0.000
Distance*seal (interaction)	1	9.696	4.83	0.033
Error	46	2.008		
Total	49			

IV. DISCUSSION

Both harbor seals were tested within the same sessions, so the 3-4 dB differences in their hearing thresholds for pile driving sounds were due to differences in the seals' hearing sensitivity, and not due to differences in equipment, equipment settings, methodology, personnel, or background noise. Based on the hearing thresholds of the individual harbor seals (Kastelein *et al.*, 2009a,b), the thresholds for the pile driving sounds recorded at two distances were expected to be the same. The present study confirms this prediction. Based again on the hearing thresholds of the individual seals (Kastelein *et al.*, 2009ab), the thresholds of seal 01 were expected to be ~2 dB lower than those of seal 02. The present study confirmed that the hearing of seal 01 was more sensitive than that of seal 02 for the pile driving sounds. The differences between the seals were 3-4 dB for the 50% thresholds based on any sound in the series, and 3-4 dB for the thresholds based on the first sound. Seal 02 never detected the pile driving sounds below a SEL of 42 dB re 1 μPa^2s, whereas seal 01 sometimes detected them at 37 dB re 1 μPa^2s (**Fig. 4**).

The 50% detection thresholds were measured for attentive harbor seals listening for familiar sounds, in the direction of (assumed) maximum hearing sensitivity (sound coming from in front of the seal). Detection thresholds would be higher for inattentive harbor seals and for sounds coming from other directions.

The small (but audible to the human ear) differences in spectrum between the played back sounds recorded at 100 m and 800 m (**Fig. 3**) did not result in clear differences in the hearing thresholds of the harbor seals for these two sounds (only 1 dB in seal 01, which is probably of little biological significance). If pile driving sounds had been recorded further away from the source, the hearing thresholds may have been different, because larger differences in the sounds' spectra and duration would have occurred due to increased absorption and reflection.

Before this study, it took a long time for the harbor seals to understand that the played back pile driving sounds were the stimuli they had to react to, and several weeks for their hearing thresholds to stabilize. In comparison, the hearing thresholds of a harbor porpoise (*Phocoena phocoena*) for the same sounds (Kastelein *et al.*, 2013) were stable (though much higher: SEL ~ 69 dB re 1 μPa^2s for any sound in the series, and ~ 73 dB re 1 μPa^2s for the first sound only) within a few sessions (one day). This may have been because the seals could hear low frequency broadband transient sounds which were not part of the hearing test sessions, caused by very occasional distant activities such as pile driving, closing of a lock, and unloading of materials from trucks. In contrast, harbor porpoise hearing is poor for low-frequency sounds (Kastelein *et al.*, 2010b).

The present study showed that the hearing threshold was lower when the animals were exposed to multiple strike sounds than it would be if they were exposed to a single strike sound. It takes ~3000 to 5000 strikes to drive a monopile for a wind turbine into the sediment, so the audibility of pile driving sounds to harbor seals can best be estimated from the detection threshold based on any sound in the series found in the present study.

As the received SEL approached the 50% hearing broadband threshold levels, the lower the received level, the later within the series of strike sounds the seals responded. This could be because, at low levels, the animals waited for another sound to confirm their first suspicions of the presence of a pile driving series. The sounds were produced at regular intervals, so the harbor seals could focus on the next moment when they expected a sound.

The pile driving sounds used in the present study served as examples. Depending on properties of the pile (diameter, length, shape, wall thickness, depth in the sediment, etc.), environment (substrate, water depth, etc.), and propagation conditions, the spectra, duration and level of actual pile driving sounds vary (though the spectra of the pile driving sounds played back in the present study resembled those of sounds recorded under certain conditions tens of km from an offshore pile driving site). The present study shows that the harbor seal's unmasked hearing threshold level for pile driving sounds is many orders of magnitude (ca. 130 dB) lower than the level measured at a distance of 800 m from an offshore pile driving location (see Table I). This suggests that pile driving sounds are audible to harbor seals at distances in the order of hundreds of kilometers from pile driving sites, depending on the actual propagation conditions and the masking of the sounds by ambient noise.

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