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for playbacks of multiple pile driving strike sounds**

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Authors:
Dr. ir. Ron Kastelein (SEAMARCO)
Lean Hoek (SEAMARCO)
Robin Gransier (SEAMARCO)
Dr. Christ de Jong (TNO)

Commissioners:
Netherlands Ministry of Economic Affairs
Netherlands Ministry of Infrastructure and the Environment

Via IMARES
Dr. ir. Erwin Winter Institute for Marine Sciences and Ecosystem Studies
IMARES
PO Box 68
1970 AB IJmuiden
e-mail: erwin.winter@wur.nl
url: www.wageningenimares.wur.nl
tel: +31 (0) 317 487115

Contractor:

Dr. ir. R. A. Kastelein
Director & owner
SEAMARCO (Sea Mammal Research Company)
Applied research for marine conservation
Julianalaan 46
3843 CC Harderwijk
The Netherlands
Tel (Office): +31-(0)341-456252
Tel (Mobile): +31- (0)6-46-11-38-72
Fax: +31-(0)341-456732
E-mail: researchteam@zonnet.nl

Hearing thresholds of a harbor porpoise (*Phocoena phocoena*) for playbacks of multiple pile driving strike sounds

Ronald A. Kastelein[a)], Lean Hoek, Robin Gransier
Sea Mammal Research Company (SEAMARCO), Julianalaan 46, 3843 CC Harderwijk, The Netherlands

Christ A. F. de Jong,
TNO, Acoustics and Sonar, Oude Waalsdorperweg 63, 2597 AK Den Haag, The Netherlands

[a)] Author to whom correspondence should be addressed. Electronic mail: researchteam@zonnet.nl

Abstract

Pile driving is presently the most common method used to attach wind turbines to the sea bed. To assess the impact of pile driving sounds on harbor porpoises, it is important to know at what distance these sounds can be detected. Using a psychophysical technique, a male porpoise's hearing thresholds were obtained for series of five pile driving sounds (inter-pulse interval 1.2-1.3 s) recorded at 100 and 800 m from the pile driving site, and played back in a pool. The 50% detection threshold sound exposure levels (SELs) for the first sound of the series (no masking) were 72 (100 m) and 74 (800 m) dB re 1 $\mu Pa^2 s$. Multiple sounds in succession (series) caused a ~5 dB decrease in hearing threshold; the mean 50% detection threshold SELs for any sound in the series were 68 (100 m) and 69 (800 m) dB re 1 $\mu Pa^2 s$. Depending on the actual propagation conditions and background noise levels, the results suggest that pile driving sounds are audible to porpoises at least at tens 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 negative effects of sound from activities such as pile driving on marine mammals. Sound is particularly important for marine mammals, as it is used for orientation and communication and to locate prey, conspecifics and predators (NRC, 2003). The harbor porpoise (*Phocoena phocoena*) may be negatively influenced by pile driving sounds. It has a wide distribution area in the coastal waters of the temperate zone of the northern hemisphere. Wind farms are often built on the continental shelf, because of the shallow water there and the relatively short distance between the wind farms and electricity users.

As a first step towards assessing the impact of pile driving sounds on harbor porpoises, it is important to determine their hearing thresholds for these sounds. The underwater hearing of harbor porpoises has been tested behaviorally (Andersen, 1970; Kastelein *et al*., 2002; 2009; 2010; Kastelein and Wensveen, 2008) and with the Auditory Evoked Potential technique (Popov *et al*., 1986; Bibikov, 1992; Lucke *et al*., 2007). The test signals used in these studies were pure tones or narrow-band frequency-modulated sweeps. In contrast to these sounds, impulsive sounds, such as pile driving strike sounds, are broadband and of short duration. Pulse duration affects audibility (Kastelein *et al*., 2010). Porpoise tonal detection thresholds decrease with frequency up to around 125 kHz, so the high frequency components in impulsive sounds may influence their detection threshold. The harbor porpoise hearing thresholds for slightly wider-band signals, such as 1.43-1.33 kHz, 1-2 kHz and 6-7 kHz sonar sweeps, are close to those for the tonal signals (Kastelein *et al*., 2011 a, b). A study of the hearing threshold of a harbor porpoise for an impulsive sound (a playback of a detonation pulse; Kastelein *et al*., 2012) showed that the porpoise's hearing threshold for impulsive sounds of shorter duration than the integration time of its hearing could be estimated from its short-duration tonal signal audiogram, if the sound exposure level (SEL), rather than the sound pressure level (SPL) is used to quantify the sounds' level.

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

II. Materials and Methods

A. Study animal

The male harbor porpoise used in this study (ID no. 02) had participated in previous psychoacoustic studies (Kastelein *et al.*, 2009, 2010, 2011a,b). During the present study he was 4.5 years old, his body weight was around 37 kg, his body length was 142 cm, and his girth at axilla was approximately 72 cm. He received between 2 and 3 kg of thawed fish per day, equally divided over four meals. Variation in the animal's hearing test performance was minimized by making weekly adjustments (usually in the order of 100 g) to his daily food ration, based on his 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, The Netherlands. Its location is remote and quiet, and was specifically selected for acoustic research. The animal was kept in a pool complex designed and built for acoustic research, consisting of an outdoor pool (12 × 8 m; 2 m deep) connected via a channel (4 × 3 m; 1.4 m deep) to an indoor pool (8 × 7 m; 2 m deep). Details of the study area are described by Kastelein *et al*. (2010).

The equipment used to produce sound stimuli was housed out of sight of the study animal. The listening station was at the end of a 3 cm diameter water-filled polyvinylchloride tube. This positioned the porpoise's external auditory meatus 2 m from the sound source, 1 m below the water surface. To allow the animal's position at the listening station to be checked, he 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.

C. Background noise and stimuli level calibration measurements

Great care was taken to make the porpoise's 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 level in the pool was very low (see Kastelein *et al*., 2010).

Prior to the tests, the received SEL (in dB re 1 μPa^2s) of the played back pile driving sounds was measured, in the absence of the porpoise, at the position of the porpoise's head during the hearing tests. This calibration was conducted with two hydrophones, one at the location of each auditory meatus of the porpoise when it was positioned at the listening station. The auditory meatus was used as a clearly visible and defined reference point which is only ca. 4 cm from the area with the best sound conduction to the ear (the side of each mandible). The SEL between the two locations varied by 0-2 dB. The average SEL of the two hydrophones was used to calculate the detection thresholds. During trials, the porpoise'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 at levels of around 20 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 by Kastelein *et al*., 2010).

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 distance on attenuation and the change in spectrum (**Figs. 1a and 2a; Table I**). Ninety % of the energy in the individual sounds was contained in the 63 Hz to 400 Hz 1/3-octave bands. The recordings were sampled at 88.2 kHz and high-pass filtered at 50 Hz. Here, the term 'sound' is used to refer to the individual pulses making up the series, the term 'series' is used to refer to a sequence of five pulses.

The digitized original recordings of series of 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) which 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.* (2010).

The output of the transducer (resulting in the played back sounds) was recorded 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 porpoise, 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) as quantified for the five sounds during the calibration measurements are given in **Table I**. The original recordings and played back sounds had some characteristic features in common, and the duration of both the original recordings and played back sounds was less than the integration time of the porpoise's hearing system for sounds in the frequency range between 250 Hz and 8 kHz (>180 ms; Kastelein *et al.*, 2010). However, the spectrum of the played back sounds differed from that of the original recordings (**Fig. 3**). 90% of the energy in the played back sounds was contained in the 800 Hz to 2 kHz 1/3-octave bands. Below 1 kHz, the original recordings could not be reproduced efficiently due to the characteristics of the projector and, to some extent, due to the shallow water in the pool. Above 5 kHz, measurement of the played back sounds was hampered by electronic noise in the measurement system. To eliminate electronic noise, a digital filter (3^{rd} 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.

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 during the calibration. 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)	Inter-pulse-interval (s)	t_{90} (ms)	$p_{z\text{-}p}$ (Pa)	SEL (dB re 1 μPa^2s)
Original (100 m)	380	51	1.2	47 (± 17)	10000 (± 1000)	177 (± 1)
Original (800 m)	690	46	1.3	46 (± 8)	5000 (± 500)	171 (± 1)
Played back (100 m)	-	51	1.2	99 (± 14)	1.9 (± 0.1)	102 (± 1)
Played back (800 m)	-	46	1.3	128 (± 6)	1.3 (± 0.3)	97 (± 1)

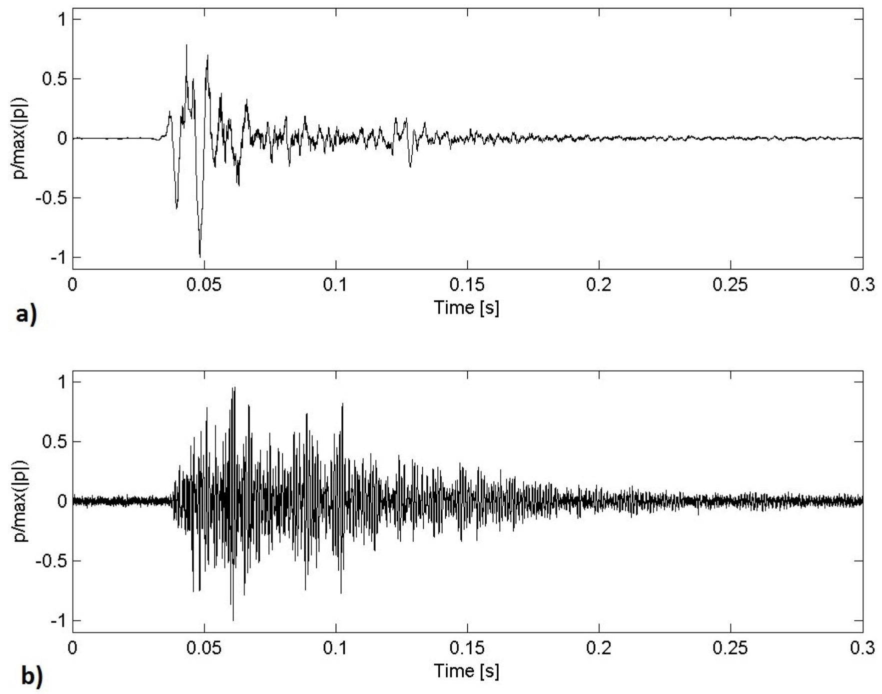

FIG. 1. Waveform of a single pile-driving sound recorded at 100 m from the pile driving site (a), and of the played back sound in the pool (b). The amplitude of the sound pressure is scaled to the maximum absolute value of instantaneous sound pressure.

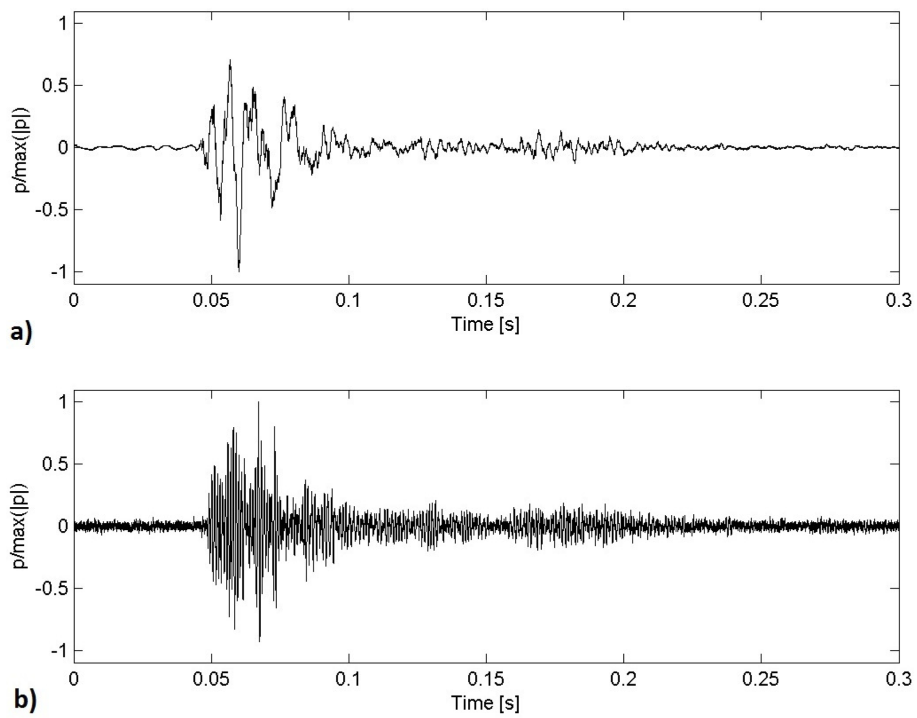

FIG. 2. Waveform of a single pile-driving sound recorded at 800 m from the pile driving site (a), and of the played back sound in the pool (b). The amplitude of the sound pressure is scaled to the maximum absolute value of instantaneous sound pressure.

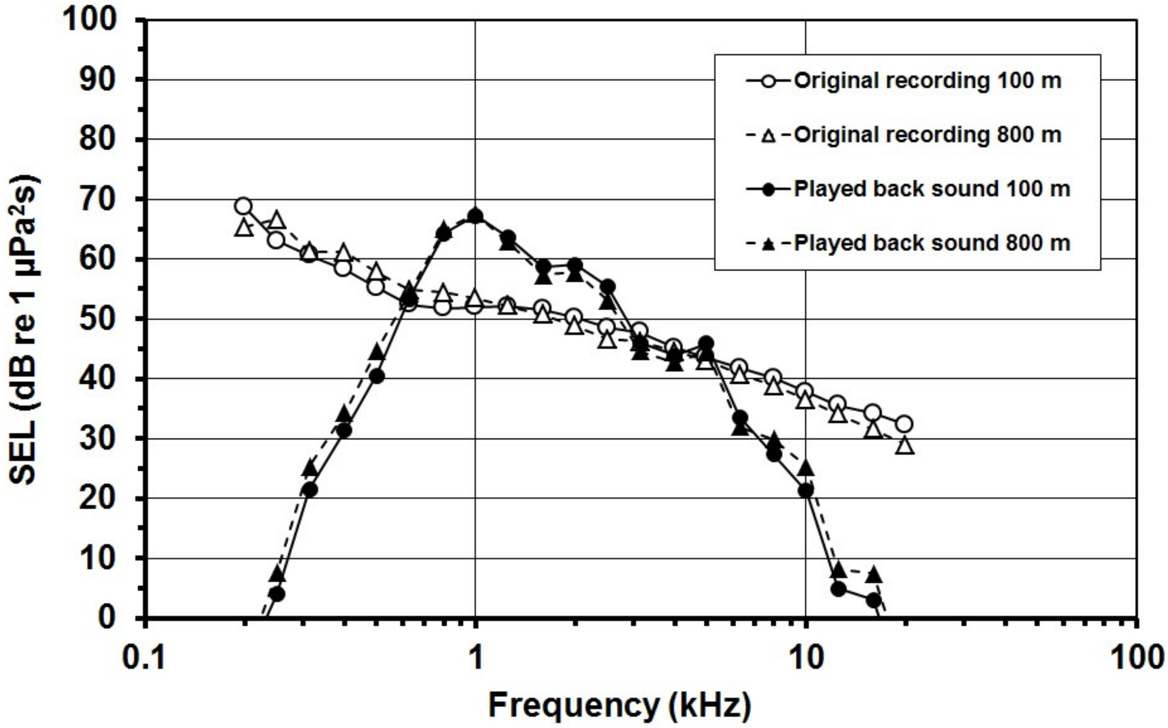

FIG. 3. The 1/3-octave band spectra of the SEL (over the 90% energy duration of the sounds) of the original and played back pile driving sounds in the pool. All spectra are scaled to the same total unweighted broadband SEL of 74 dB re 1 μPa^{2}s in the 200 Hz to 20 kHz 1/3-octave bands.

E. Experimental procedure

A psychophysical method was used to determine the hearing thresholds (for details see Kastelein *et al*., 2010). A trial began with the animal at the start/response buoy. In signal-present trials, the porpoise stationed, then had to wait for a period of random duration between 6 and 12 s (established via a random number generator), before the signal operator started the series of five pile driving sounds. If the animal detected a sound, it was trained to leave the station ("go" response) at any time during the transmission of the sounds and return to the start/response buoy. When each 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 during which sound in the series the animal responded. 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 porpoise a fish reward. The operator recorded the sound (strike) number to which the porpoise 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 him back to the start/response buoy. No reward was given.

The sounds' amplitude was varied according to the 1-up 1-down (2 dB steps) adaptive staircase method. This conventional psychometric technique (Robinson and Watson, 1973) results in a 50% correct detection threshold (Levitt, 1971). The amplitude in the first trial of the session was approximately 10 dB above the detection threshold determined during pretests. The series of played back pile driving sounds were tested until 333 reversal pairs had been obtained (in 32 sessions) per recording distance. To prevent the animal's learning process from affecting the threshold levels, the series of sounds recorded at the two distances were tested in random order. Sessions consisted of 2/3 signal-present and 1/3 signal-absent trials offered in quasi random order, but there were never more than three consecutive signal-present or signal-absent trials. Two or three experimental sessions per day were conducted (at 0830, 1330 and 1600 h) between May and July 2010.

F. Determination of detection thresholds

Hearing thresholds are usually expressed as SPLs. However, the SPL is highly 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 single-sound SEL (10 times the 10 base log of the time integral [seconds] of the squared pressure over the duration of the sound, in dB re 1 μPa^2s) is proportional to the total energy in a sound. The SEL is used here to characterize the 50% detection threshold for sounds that are shorter than the integration time of the hearing system.

A switch from a test signal level at which the porpoise responded to one of the five sounds (a hit), to a level that it did not respond to (a miss), and *vice versa*, is called a reversal. The mean 50% detection threshold for series of five pile driving sounds was determined by calculating the mean single-sound SEL of all reversal pairs for each recording distance.

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.

III. RESULTS

The pre-stimulus response rates (based on both signal-present and signal-absent trials) were 2% (100 m) and 5% (800 m). At and above an SEL of 74 dB re 1 μPa^2s (SPL: 84 dB re 1 μPa, averaged over signal duration (t_{90}): 99 ms), the porpoise always detected the first sound in the series recorded at 100 m. Below that level, it sometimes required more sounds (**Fig. 4a**). At and above an SEL of 75 dB re 1 μPa^2s (SPL: 84 dB re 1 μPa, averaged over signal duration (t_{90}): 128 ms), the porpoise always detected the first sound in the series recorded at 800 m. Below that level, it sometimes required more sounds (**Fig. 4b**), but seldom more than three. The 50% detection thresholds for the first sound in each series was at a single-sound broadband SEL of 72 dB re 1 μPa^2s (SPL: 82 dB re 1 μPa, averaged over signal duration (t_{90}): 99 ms) for the sounds recorded at 100 m, and 74 dB re 1 μPa^2s (SPL: 84 dB re 1 μPa, averaged over signal duration (t_{90}): 99 ms) for the sounds recorded at 800 m. Multiple sounds in succession caused a ~5 dB decrease in hearing threshold; the 50% detection thresholds for any sound in the series were: 68 dB re 1 μPa^2s (SPL: 78 dB re 1 μPa, averaged over signal duration (t_{90}): 99 ms) for the sounds recorded at 100 m, and 69 dB re 1 μPa^2s (SPL: 78 dB re 1 μPa, averaged over signal duration (t_{90}): 128 ms) for the sounds recorded at 800 m.

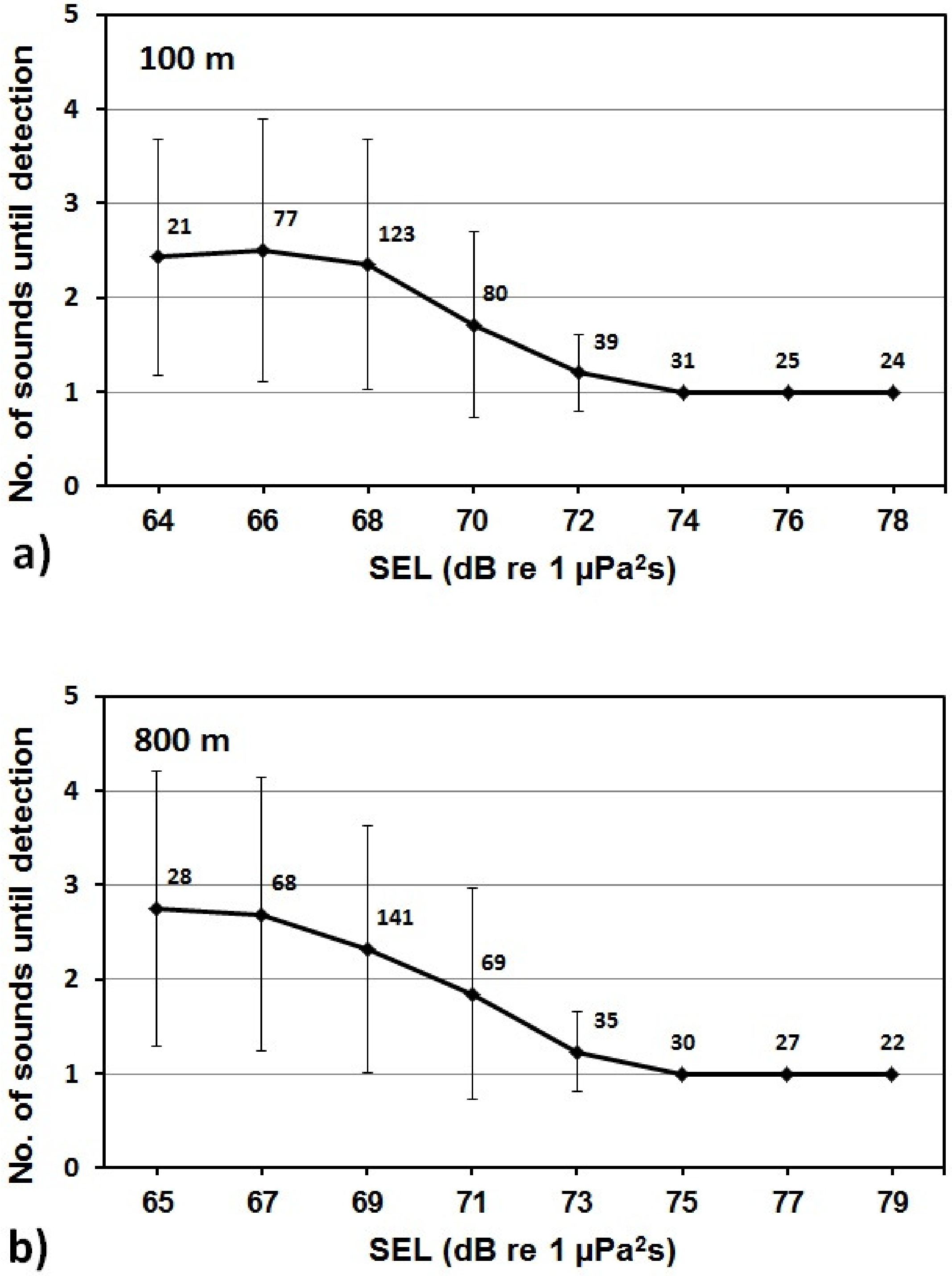

FIG. 4. The received broadband sound exposure level (SEL based on a single pulse) in relation to the mean pile driving sound number (of the series of five sounds) which the harbor porpoise detected (the bars indicate the ± standard deviation, the numbers in the graph are the sample sizes which vary due 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 from the pile driving location. For SPL (dB re 1 μPa), add ~9 dB to the SEL values.

IV. DISCUSSION

The data of the present study are derived from only one animal, and so should be treated with caution. However, his hearing thresholds were similar to those of two other young male harbor porpoises (Kastelein *et al*., 2002; 2009; 2010), so the study animal probably had normal hearing for porpoises of its age, and the thresholds found in the present study for the played back pile driving sounds are probably representative for young harbor porpoises with good hearing.

The pre-stimulus response rates (based on both signal-present and signal-absent trials) were in the same range as in previous psychoacoustic hearing studies with this animal (Kastelein *et al*., 2010, 2011a,b; 2012). The pre-stimulus response rate of this porpoise is always very low, because the pool is very quiet, and because the porpoise is very co-operative (due to his personality and the very careful management of his energetic demands).

The 50% detection threshold was measured for an attentive porpoise listening for a familiar sound, in the direction assumed to be that of maximum hearing sensitivity (sound coming from in front of the porpoise; Kastelein *et al*., 2005). The detection thresholds would be higher for inattentive porpoises and for sounds coming from other directions.

The small (but audible to the human ear) differences in spectrum between the played back sounds that were recorded at 100 m and 800 m from a North Sea pile driving location (**Fig. 3**) did not result in significant differences in the hearing thresholds of the porpoise for these two sounds. If pile driving sounds had been recorded at a greater distance apart, the hearing thresholds would probably have been different, because larger differences in the sounds' spectra and duration would have occurred due to increased absorption and reflection.

The present study showed that the hearing threshold was lower when the animal was exposed to multiple strike sounds than when he was only exposed to a single strike sound. Thus, because it takes ~3000 to 5000 strikes to drive a monopile for a wind turbine into the sediment, the audibility can best be estimated from the detection threshold based on any sound in the series found in the present study. 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 and level of actual pile driving sounds vary. The porpoise's unmasked hearing threshold levels for pile driving sounds are many orders of magnitude lower (ca. 100 dB) than the SPLs 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 porpoises at least at tens of km from pile driving sites, depending on the propagation conditions and the masking of the sounds by ambient noise. In agreement with this, Tougaard *et al* (2009) reported that harbor porpoises were deterred at least 21 km from a pile driving site. At that distance, the SPL must have been several dB above the hearing threshold to cause the behavioral response. The effects of pile driving sounds on harbor porpoises are thus far-reaching.

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Andersen, S. (**1970**). "Auditory sensitivity of the harbour porpoise, *Phocoena phocoena*". in *Investigations on Cetacea.* Edited by G. Pilleri, (Institute for brain research, Bern), Vol. 2, 255-259.

Bibikov, N. G. (**1992**). "Auditory Brainstem Responses in the Harbor Porpoise (*Phocoena phocoena*)," in *Marine Mammal Sensory Systems*, Edited by J.A. Thomas, R.A. Kastelein, and A.Ya. Supin (Plenum Press, New York), pp. 197-211.

Kastelein, R. A., Bunskoek, P., Hagedoorn, M., Au, W. W. L., and de Haan, D. (**2002**). "Audiogram of a harbor porpoise (*Phocoena phocoena*) measured with narrow-band frequency-modulated signals," J. Acoust. Soc. Am. **112**, 334-344.

Kastelein, R. A., Janssen, J., Verboom, W. C., and de Haan, D. (**2005**). "Receiving beam patterns in the horizontal plane of a harbor porpoise (*Phocoena phocoena*)," J. Acoust. Soc. Am. **118**, 1172-1179.

Kastelein, R. A., and Wensveen, P. J., (**2008**). "Effect of two levels of masking noise on the hearing threshold of a harbor porpoise (*Phocoena phocoena*) for a 4.0 kHz signal," Aquatic Mammals **34**, 420-425.

Kastelein, R. A., Wensveen, P. J., Hoek, L., Au, W. W. L., Terhune, J. M., de Jong, C. A. F. (**2009**). "Critical ratios in harbor porpoises (*Phocoena phocoena*) for tonal signals between 0.315 and 150 kHz in random Gaussian white noise", J. Acoust. Soc. Am. **126**, 1588-1597.

Kastelein, R. A., Hoek, L., de Jong, C. A. F, and 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," J. Acoust. Soc. Am. **128**, 3211-3222.

Kastelein, R. A., Hoek, L., and de Jong, C. A. F. (**2011a**). "Hearing thresholds of a harbor porpoise (*Phocoena phocoena*) for sweeps (1-2 kHz and 6-7 kHz bands) mimicking naval sonar signals," J. Acoust. Soc. Am. **129**, 3393-3399.

Kastelein, R. A., Hoek, L., and de Jong, C. A. F. (**2011b**). "Hearing thresholds of a harbor porpoise (*Phocoena phocoena*) for helicopter dipping sonar signals (1.43-1.33 kHz) (L)," J. Acoust. Soc. Am. **130**, 679-682.

Kastelein, R. A., Gransier, R., Hoek, L., and de Jong, C. A. F. (**2012**). "The hearing threshold of a harbor porpoise (*Phocoena phocoena*) for impulsive sounds (L)", J. Acoust. Soc. Am. **132**, 607-610.

Levitt, H. (**1971**). "Transformed up-down methods in psychoacoustics," J. Acoust. Soc. Am. **49**, 467-477.

Lucke, K., Lepper, P. A., Hoeve, B., Everaarts, E., van Elk, N., and Siebert, U. (**2007**). "Perception of low-frequency acoustic signals by a harbour porpoise (*Phocoena phocoena*) in the presence of simulated offshore wind turbine noise," Aquatic Mammals, **33**, 55-68.

Madsen, P. T. (**2005**). "Marine mammals and noise: Problems with root mean square sound pressure levels for transients", J. Acoust. Soc. Am. **117**, 3952-3957.

NRC (National Research Council) (**2003**). “Ocean noise and marine mammals”. National Academic Press, Washington D.C. pp. 192.
Plomp, R. (**1961**), “Hearing threshold for periodic tone pulses”, J. Acoust. Soc. Am. **33**, 1561-1569.
Popov, V. V., Ladygina, T. F., and Supin, A. Ya. (**1986**). "Evoked potentials of the auditory cortex of the porpoise, *Phocoena phocoena*," J. Comp. Physiol. (A) **158**, 705-711.
Robinson, D. E., and Watson, C. S. (**1973**). “Psychophysical methods in modern Psychoacoustics,” in *Foundations of Modern Auditory Theory*, edited by J. V. Tobias (Academic, New York), Vol. 2, 99-131.
Tougaard, J., Carstensen, J., Teilmann, J., Skov, H., and Rasmussen, P. (**2009**).“Pile driving zone of responsiveness extends beyond 20 km for harbor porpoises (*Phocoena phocoena*) (L.),” J. Acoust. Soc. Am. **126**, 11-14.