Aquatic Mammals 2018, *44*(1), 92-99, DOI 10.1578/AM.44.1.2018.92

Swimming Speed of a Harbor Porpoise (*Phocoena phocoena*) During Playbacks of Offshore Pile Driving Sounds

Ronald A. Kastelein,[1] Shirley Van de Voorde,[1] and Nancy Jennings[2]

[1]*Sea Mammal Research Company (SEAMARCO), Julianalaan 46, 3843 CC Harderwijk, The Netherlands*
E-mail: researchteam@zonnet.nl
[2]*Dotmoth, 1 Mendip Villas, Crabtree Lane, Dundry, Bristol BS41 8LN, UK*

Abstract

The loud sounds produced under water during offshore percussion pile driving for the construction of wind turbines may affect harbor porpoises (*Phocoena phocoena*). Kastelein et al. (2013b) exposed a porpoise in a quiet pool to playbacks of underwater pile driving sound at several mean received sound pressure levels (SPLs; range: 130 to 154 dB re 1 µPa) and suggested that harbor porpoises at sea swim away from offshore pile driving locations (moving tens of km), thus reducing their received SPL. The speed at which they swim both determines the acoustic exposure and impacts the energetic costs of a behavioral response. Therefore, information on swimming speed is important for estimating the potential impact of pile driving sounds on the hearing, the energetics, and the population dynamics of harbor porpoises. The video recordings from the Kastelein et al. (2013b) study were analyzed for swimming speed. During quiet baseline periods, the mean swimming speed of the porpoise was 4.3 km/h, and he swam a mean distance of 2.2 km in 30 min. Even at the lowest SPL tested (130 dB re 1 µPa), his mean swimming speed was significantly greater than during baseline periods. At the highest SPL (154 dB re 1 µPa), his mean swimming speed was 7.1 km/h, and he swam a mean distance of 3.6 km in 30 min. Swimming speed did not decline significantly during the 30-min test periods, and a speed of ~7 km/h appears to be sustainable for harbor porpoises.

Key Words: acoustics, behavior, disturbance, habitat, marine mammals, noise, odontocete, offshore wind farms, temporary threshold shift, wind turbines, swimming speed

Introduction

Coastal waters support high densities of marine fauna and are heavily used by humans producing noise through, for example, oil and gas industry operations and, more recently, the construction of wind turbines. Although alternative methods of attaching wind turbines to the sea floor are being investigated, installation still commonly involves percussion pile drivers which produce loud impulsive sounds. Offshore pile driving with hydraulic hammers for wind turbine installation at sea produces impulsive sounds at a rate of ~35 to 65 strikes/min, and placing one mono-pile may take a few hours. The duration of the signal and sound pressure level (SPL) of the sounds depend on the distance from the pile at which they are measured. The sound energy released into the environment during percussion pile driving can be reduced by noise mitigation systems such as cofferdams or bubble screens (Bellmann, 2014).

The high-amplitude sounds produced under water during offshore pile driving may affect marine mammals (Bailey et al., 2010). A marine mammal that is potentially affected is the harbor porpoise (*Phocoena phocoena*) because it has a wide distribution in the coastal waters of the northern hemisphere (Bjorge & Tolley, 2008) and because this small odontocete has hearing that is acute and functional over a very wide frequency range (Kastelein et al., 2002, 2009, 2010, 2017). Kastelein et al. (2013a) determined the 50% hearing threshold of a harbor porpoise for playbacks of pile driving sound when background noise levels were low (below levels occurring during Sea State 1). The 50% detection threshold sound exposure levels (SELs) for the first sound of the series (no masking) was ~73 dB re 1 μPa^2s (see Kastelein et al., 2013a, for signal parameters).

Multiple sounds in succession (series) caused a ~5 dB decrease in hearing threshold. These hearing thresholds, together with propagation conditions and background noise levels, can be used to calculate the distance to which piling sound is audible to harbor porpoises. However, ecologically, it is more important to discover at which SPL pile driving sounds become uncomfortable to harbor porpoises or at which SPL their behavior changes in response to the sounds.

Only when a sound has an effect on the physiology and/or behavior of an animal can it directly affect its chance of survival or reproduction. Kastelein et al. (2013b) exposed a porpoise in a quiet pool to playbacks of underwater pile driving sound (46 strikes/min; signal duration: 126 ms) at five SPLs to determine the behavioral response threshold SPL. The results suggested that, at sea, harbor porpoises are likely to move tens of km (~20 km, depending on the propagation conditions and ambient noise) away from offshore pile driving locations; this estimated distance is in the same order of magnitude as that observed in wild harbor porpoises near pile driving sites (Carstensen et al., 2006; Tougaard et al., 2009; Brandt et al., 2011; Dähne et al., 2013; Haelters et al., 2014).

Harbor porpoises swimming away from piling areas at sea reduce their received SPL of the piling sounds. The speed at which they swim away determines both the acoustic energy received by their ears (cumulative SEL) and the energetic cost of locomotion—the faster they swim, the greater the energetic cost. Information on swimming speed and endurance is important for estimating the impact of pile driving sounds on both the hearing and energetics of harbor porpoises. The information can also be used to estimate the effect of pile driving sounds on harbor porpoise population dynamics. The Population Consequences of Acoustic Disturbance (PCAD) framework (National Research Council, 2005) was implemented to generate the Interim Population Consequences of Disturbance (iPCoD) model (King et al., 2015) and the Disturbance Effects of Noise on the Harbour Porpoise Population in the North Sea (DEPONS) model (Nabe-Nielsen et al., 2014), provides an energetics-based approach to estimate population dynamics effects.

Therefore, with the above points in mind, the objective of the present study was to measure and compare the swimming speed of a captive harbor porpoise during quiet baseline periods and during 30-min exposures to playbacks of pile driving sounds at three SPLs (Kastelein et al., 2013b). These outputs can provide useful insights into assessments of the energetic costs of disturbance for individuals and contribute to population-level model assessments.

Methods

Study Animal and Facility

The male study animal, identified as Porpoise 02, was 7 y old at the time of the study; his body weight was around 38 kg, his body length was 146 cm, and his girth at axilla was ± 73 cm. His hearing was assumed to be representative of animals his age of the same species; it was similar to that of two other young harbor porpoises (Kastelein et al., 2002, 2009, 2010, 2017). He received four meals of fish per day.

The study animal was kept at the SEAMARCO Research Institute, the Netherlands, in a pool complex specifically designed and built for acoustic research, consisting of an indoor pool (described in detail by Kastelein et al., 2010) and an outdoor pool (12 × 8 m, 2 m deep) in which this study was conducted (Figure 1). The walls of the outdoor pool were made of plywood covered with polyester and 3-cm thick coconut mats with their fibers embedded in 4-mm thick rubber (reducing reflections mainly above 25 kHz). The bottom was covered with sand. The water circulation system and the aeration system for the biofilter were made as quiet as possible, and they were switched off before sessions and kept off during sessions so that there was no current in the pool. The equipment operator was out of sight of the study animal in a research cabin next to the pool (Figure 1; see also Kastelein et al., 2013b).

Equipment, Playback Sounds, and Experimental Procedure

The study animal's behavior was filmed from above by a waterproof camera (Conrad – 750940) with a wide-angle lens and a polarizing filter to prevent saturation of the video image by glare from the water surface. The camera was placed on a pole 9 m above the water surface on the northwestern side of the pool (Figure 1). The entire surface of the pool was captured on the video image. The output of the camera was fed through a video multiplexer (MX-8 – CSX) which added the time and date to the images. Thereafter, the output was digitized by an analog-to-digital converter (König – grabber) and stored on a laptop computer (Medion – MD96780).

A recording of pile driving sound sequences made at sea from an offshore wind farm was played back in the pool as a WAV file. For details of the playback sounds, the sound transmitting and recording equipment, and the background noise, see Kastelein et al. (2013b). The SPL distribution in the pool was measured at 77 locations in the horizontal plane and at three depths. Because Porpoise 02 used the entire pool during the test periods with pile driving sound, the mean received

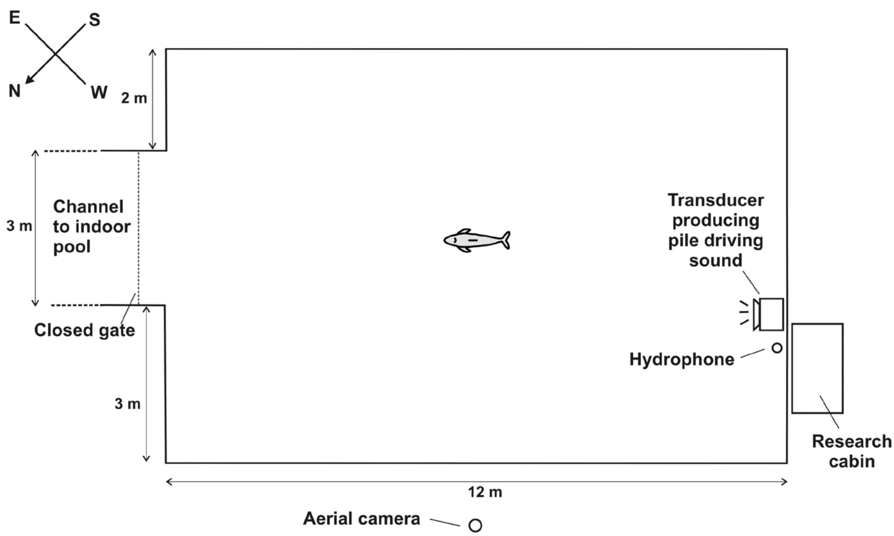


Figure 1. Top scale view of the outdoor pool study facility, showing the study animal, the aerial camera, the underwater transducer producing the pile driving sounds, and the hydrophone used to listen to the pile driving sounds and ambient noise. Also shown is the research cabin which housed the video and audio equipment and the operator.

SPL per source level was calculated from all 231 measurements. Per depth, levels decreased slightly with increasing distance from the transducer (see Kastelein et al., 2013b, for details). The pile driving sound sequences were played back at three source levels within a 24 dB range (12 dB steps), resulting in mean received root-mean-square SPLs of 130, 142, and 154 ± 3 dB re 1 µPa; single-strike (t_{90}) SELs of 121, 133, and 145 ± 2.7 dB re 1 µPa^{2}s; and zero-to-peak SPLs of 145, 157, and 169 ± 3 dB re 1 µPa (Kastelein et al., 2013b). The levels near a pile driving site at sea are much higher than those that could be produced in the pool.

The transducer producing the playback sequences was positioned in the water at the southwestern end of the pool at the start of each day (Figure 1). Sessions consisted of a 30-min baseline period (no sound emission), followed by a pause of random length (no sound emission; no recordings), followed by a 30-min test period (piling sound sequence emission). The pause was included so that the animal could not predict when the test period would start. It takes ~2 h to drive a mono-pile into the substrate, but test periods were only 30 min long to minimize negative impact or stress. Generally, one session was conducted per day, 5 d/wk, beginning between 0900 and 1600 h. During the test and baseline periods, only the operator in the research cabin was allowed within 10 m of the pool, and she sat very still.

During each test period, the playback of pile driving sounds was transmitted at one of the three SPLs, and each level was tested in ten periods, resulting in 30 test periods in all. The three levels were tested in random order. To prevent potential masking of the sounds by background noise, tests were not carried out during rainfall or when wind speeds were above Beaufort 4 (during the tests, the background noise level was below that observed at sea during Sea State 1; Knudsen et al., 1948). The data collection period was between June and August 2012.

Analysis

Software (*Kinovea*) was used to measure the distance Porpoise 02 swam in each session from the video recordings by tracking the animal automatically frame-by-frame. In ~10% of the videos, the study animal was difficult to track due to glare, shadows, or waves, so the playback speed was reduced by 25 to 200% to allow easier manual tracking in sections where the porpoise could not be tracked automatically. The 30-min video recordings were analyzed in sections of 10 min to determine whether Porpoise 02's speed changed during the test period. Images of the tracked path in each 10-min section were stored. Calibration was done by means of the 1 m marks on the sides of the pool. To account for the perspective of the images, the calibration was done both from the side of the pool nearest to the camera and from the side farthest from the camera; the mean was used for the calculations. In addition to the ten 30-min test periods per SPL, data were collected from ten random baseline periods.

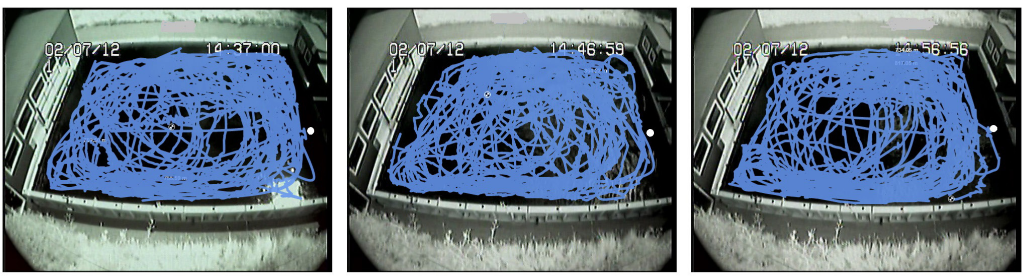
Porpoise 02's swimming speed was calculated from the distance he traveled. For statistical analysis, we considered only the swimming speed. An ANOVA on swimming speed was conducted with the crossed factors level (SPL, including the baseline: SPL = 0) and 10-min section. The interaction term between the two factors was initially included but was removed from the final analysis as it was not significant. Data conformed to the assumptions of the tests, and the level of significance was 5% (Zar, 1999).

In addition to the swimming speed and distance traveled, the respiration rates were also counted in the baseline and test periods. These data have already been reported by Kastelein et al. (2013b). Respiration rates for the relevant SPLs are presented in the "Results" section for comparison with the swimming speeds from the present study.

Results

During baseline periods, the mean swimming speed of Porpoise 02 was 4.3 km/h, and he swam a mean distance of 2.2 km in 30 min. The study animal used most of the pool during most of the test periods. A tracked swimming path from a representative test period at the maximum SPL tested (154 dB re 1 µPa) showed that he did not avoid the location of the underwater transducer (Figure 2). During the test periods, Porpoise 02 increased his mean swimming speed relative to during baseline periods and, thus, the mean distance he swam in the 30-min periods (Table 1; Figure 3a).

Analysis showed that Porpoise 02's swimming speed was similar in the three 10-min sections of the test periods. However, swimming speed was significantly affected by the SPL factor (Table 2). The interaction term between the two factors had been removed from the final analysis as it was not significant, showing that the combined pattern of effects of the 10-min sections and SPL was similar for all SPLs. *Post-hoc* tests showed that the



0-10 min. **10-20 min.** **20-30 min.**

Figure 2. Example of the swimming tracks of the harbor porpoise (*Phocoena phocoena*) during three consecutive 10-min sections of a 30-min test period in which he was exposed to pile driving playback sound at a mean received SPL of 154 ± 3 dB re 1 µPa (from left to right: 0 to 10 min, 10 to 20 min, and 20 to 30 min). The study animal used most of the pool and did not avoid the underwater transducer (indicated by the white dot on the right-hand side of the pool). Due to the reverberations in the pool, the SPL distribution was fairly homogenous. Pool dimensions: 12 m × 8 m; 2 m deep.

Table 1. The mean (± SD) swimming speed by the harbor porpoise (*Phocoena phocoena*) during quiet baseline periods and during the 30-min test periods in which he was exposed to pile driving playback sounds at three mean received SPLs (n = 10 for each SPL). Also included are the results of the *post-hoc* tests carried out after the ANOVA, which showed that the swimming speed was significantly affected by the SPL (Table 2). In the *post-hoc* tests, the same letters indicate the mean received SPLs between which *post-hoc* tests showed no significant difference in the swimming speed.

Mean received SPL dB re 1 µPa	Mean (±SD) swimming speed (km/h)	*Post-hoc* test
Sea State 1 (baseline)	4.3 (± 0.7)	A
130	5.3 (± 1.1)	B
142	5.6 (± 0.7)	B
154	7.1 (± 0.6)	C

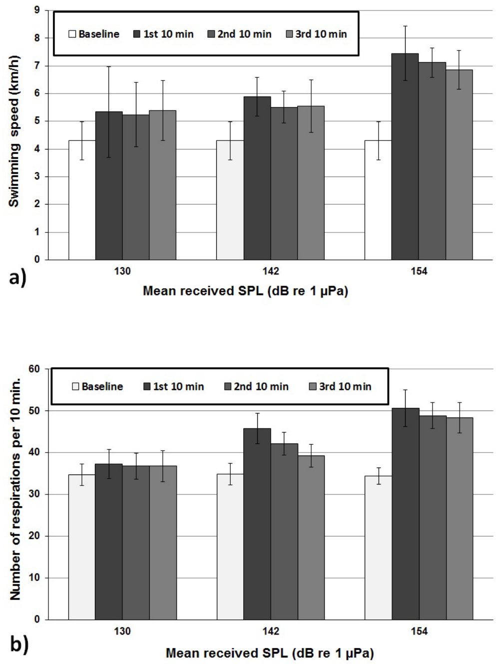


Figure 3. (a) The mean swimming speed (± SD; *n* = 10) of Porpoise 02 during baseline periods and during the first, second, and third 10-min sections of the 30-min test periods in which he was exposed to pile driving playback sounds at a mean received SPL of 130, 142, and 154 dB re 1 µPa. (b) The mean respiration rates during the same periods (selected levels from Kastelein et al., 2013b). For single-strike SELs, subtract 9 dB from the SPL levels shown.

swimming speed was significantly lower in the baseline periods and higher in periods with the highest SPL (SPL = 154 dB re 1 µPa). Swimming speed in test periods with SPL = 130 and 142 dB re 1 µPa was similar but significantly different to that in the baseline periods and in the highest exposure level periods (Table 1).

The respiration rate (reported by Kastelein et al., 2013b) showed a similar pattern as the swimming speed (Figure 3b).

Discussion

Evaluation of Experimental Approach

Only a small gradient in pile driving playback sound SPL occurred in the pool (Kastelein et al., 2013b), so Porpoise 02 used the entire pool even when he experienced the highest source level of the pile driving playback exposures (there were no relatively quiet locations to which he could swim).

Behavioral effects during exposure to pile driving sound occurred when the background noise between the impulsive sounds was very low (lower than the sound during Sea State 1, as in this study). Under higher background noise conditions, effects are expected to be less clear, as responses of harbor porpoises to sounds decrease as the signal-to-noise ratio decreases (Kastelein et al., 2011).

Within sessions, the swimming speed seemed to decrease slightly at the highest level (Figure 3a), but this was not statistically significant. When the same harbor porpoise was exposed to the same pile driving playback sounds in another study, his hearing showed a 2.2-dB temporary threshold shift after 30 min (Kastelein et al., 2016). This means that the SPL perceived by the animal was gradually reduced so that after the 30-min test period, the pile driving sound appeared to the study animal to be 2.2 dB less loud than at the start of the period.

The sound field, the sound levels (including background noise level), and the durations of baseline and test periods were appropriate for assessing the effects of the piling sounds on the swimming speed in the harbor porpoise.

Increased Swimming Speed as a Response to Pile Driving Sounds

To evaluate the impacts of pile driving sounds on harbor porpoise swimming speeds, it is important to understand how the swimming speeds observed in the present study compare to maximum known swimming speeds and to general swimming speeds, and whether the observed swimming speeds are sustainable.

It is difficult to relate the swimming speed observed during the highest SPL (7.1 km/h) to the

Table 2. Results of ANOVA to evaluate changes in the harbor porpoise's swimming speed in the 10-min sections of each test period, taking into account the SPL (included as a factor); df = degrees of freedom, Adj. MS = adjusted mean square, F = test statistic, and *p* = significance. For *post-hoc* test results, see Table 1.

Source of variation	df	Adj. MS	F	*p*
SPL	3	41.34	45.96	0.000
10-min section	2	0.45	0.51	0.601
Error	108	0.90		

maximum swimming speed of the harbor porpoise. In the 22 y in which captive harbor porpoises have been observed by the first author, including in a large floating pen (34 m × 20 m; 3.5 m deep at the sides and 5 m deep in the centre) and in the large pool used in the present study (12 m × 8 m; 2 m deep), they never swam much faster than during pile driving playback at the highest SPL used in the present study. The swimming speeds observed during pile driving playback were similar to those seen during rainfall when porpoises tend to increase their swimming speed. During rainfall in the pool used in the present study, an adult female harbor porpoise similar in size to the study animal swam at a mean speed of 5.8 km/h (SD ± 0.4 km/h; $n = 3$; measured over 5 min).

Some information on the general swimming speeds of wild harbor porpoises is available. Gaskin et al. (1975) calculated mean horizontal displacement rates of porpoises in the wild from very high frequency (VHF) transmitter tracking data and obtained swimming speeds ranging from 1.6 to 2.2 km/h (maximum 6.7 km/h). Otani et al. (2000) reported a mean horizontal swimming speed of 3.2 km/h; 90% of the time the speed was below 5.4 km/h, and the highest speed recorded was 15 km/h. Brandt et al. (2013a, 2013b) reported swimming speeds for harbor porpoises fleeing from seal scarers of between 4.7 and 11.5 km/h (mean 5.8 km/h). Linnenschmidt et al. (2013) recorded the minimum swimming speeds of three free-ranging porpoises as 8.0, 2.6, and 4.0 km/h. Although swimming speed data are scarce and difficult to compare due to differences in methodology (VHF transmitters, data loggers, and tracking routes as in the present study), circumstances (feeding, traveling, and fleeing), and ways of reporting (maximum speed, speed range, and the time a speed could be maintained), the swimming speeds observed in the present study are similar to those observed in the wild.

The harbor porpoise in the present study could maintain the maximum observed mean swimming speed (7.1 km/h) for at least 30 min. Two observations suggest that he was not performing at maximum capacity: (1) as the test periods ended, his respiration rate immediately returned to normal; and (2) within 1 min after exposure to pile driving sounds in a similar study, the same animal participated in a behavioral hearing test which required him to use subtle pectoral fin and tail fluke movements to achieve a very precise body position and stay under water for at least 1 min (Kastelein et al., 2016).

Otani et al. (2001) studied the rate of oxygen consumption and the energetic cost of locomotion in captive harbor porpoises and found that oxygen consumption increased with swimming speed according to a cubed function. The minimum cost of transport during underwater swimming in the harbor porpoise is 2.39 to 2.43 J/kg/m at an average swimming speed of between 4.7 and 5.4 km/h. However, the porpoises usually swam more slowly (thus conserving energy) and dove aerobically. This explains why harbor porpoises can dive repeatedly and continuously without resting for extended periods at the sea surface, and it suggests that a swimming speed of up to 5.4 km/h requires little energy (Otani et al., 2001).

In response to sounds, the respiration rate of the study animal showed a similar pattern as the swimming speed (Figure 3), suggesting that the parameters are correlated: greater exertion costs more energy and, thus, requires more oxygen. The respiration rate did not increase during the 30-min test periods even at the highest SPL, suggesting that the study animal could maintain a speed of 7.1 km/h relatively easily. The results from the present study suggest this speed to be sustainable for harbor porpoises for at least 30 min.

The Response Threshold for Harbor Porpoises at Sea

Harbor porpoises may flee from locations where they are exposed to pile driving sounds at broadband SPLs ≥ ~142 dB re 1 μPa under low ambient noise conditions (Kastelein et al., 2013b). This "142 dB SPL behavioral threshold" corresponds (due to the sounds' duration) to a broadband single-strike SEL threshold of ~133 dB re 1 μPa^2 s in the present study. However, the behavioral threshold SEL is probably only valid for the spectrum that the porpoises were exposed to by Kastelein et al. (2013b) and in the present study (same spectrum as in Kastelein et al., 2013b). As the distance to the piling site increases, the spectrum changes; high frequencies are more easily absorbed by sea water than low frequencies. The hearing sensitivity of harbor porpoises is frequency-dependent. Hearing is more sensitive at higher frequencies than at lower frequencies (Kastelein et al., 2017), so it is likely that the study animal of Kastelein et al. (2013b) reacted to the high-frequency components of the broadband pile driving playback sound. Therefore, it is not realistic to compare broadband SPLs at sea (Remmers & Bellmann, 2016) directly with the broadband 133 dB re 1 μPa^2 s SEL threshold. We recommend that SEL measurements should be weighted—for instance, with the weighting function proposed by the National Marine Fisheries Service (NMFS) (2016), although this weighting function is proposed to only set SEL limits to prevent permanent hearing threshold shift. Weighting of SEL may also be important in setting sound level limits to prevent behavioral disturbance.

Conclusion

In the wild, harbor porpoises have been observed swimming away from pile driving sites to distances of tens of km (Dähne et al., 2013; Haelters et al., 2014). As they move away from a sound source, harbor porpoises reduce the SPL they receive. Porpoises probably begin to swim away from a piling site before piling starts as activities such as shipping, hoisting, and positioning the pile create underwater sounds that may deter them.

Driving one mono-pile into the substrate usually takes about 2 h. Based on the swimming speed observed in the present study at a mean received SPL of 154 dB re 1 µPa (~7 km/h; a speed that is probably sustainable for harbor porpoises), a harbor porpoise that is near a pile driving site when piling begins may swim approximately 14 km away from the site during the piling activity. The increase in swimming speed during fleeing from a piling site may lead to an increase in energy expenditure and could have ecological implications for the porpoise if insufficient prey is available.

The impact of sound on hearing depends on a combination of the received SPL and the exposure duration. In modelling the impact of piling sound on harbor porpoise hearing, the exposure time is often fixed (e.g., the time it takes to drive a particular mono-pile a certain depth into the substrate), but the SPL received by a porpoise during the piling process depends on its location at the onset of piling, the local propagation conditions, and the animal's swimming speed and direction.

Acknowledgments

We thank Jesse Dijkhuizen for his help in developing the video analysis technique, and Fabian Hoekstra, Gunnar Berger, Dimitri Sprokkereef, Alwin Glas, and Iris Keurntjes for helping with the video analysis. We thank Rob Triesscheijn for making one of the figures and Bert Meijering (Topsy Baits) for providing space for the SEAMARCO Research Institute. Erwin Jansen (TNO) did the acoustic measurements. We thank Arie Smink for the construction and maintenance of the electronic equipment. We also thank Christ de Jong (TNO), Joop Bakker (RWS), Martine Graafland (RWS), Floor Heinis (Heinis Waterbeheer en Ecologie), and Cormac Booth (SMRU consulting) for their valuable constructive comments on this manuscript. Funding for this project was obtained from the Netherlands Ministry of Infrastructure and Environment (BAS-code: BO-11-018.02-011; contact Martine Graafland) and from Gemini, Buitengaats CV (PO GEM-03-185; contact Luuk Folkerts). The harbor porpoise was tested under authorization of the Netherlands Ministry of Economic Affairs, Department of Nature Management, with Endangered Species Permit FF/75A/2009/039. We thank the ASPRO group for making the porpoise available for this study.

Literature Cited

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

Bellmann, M. A. (2014). *Overview of existing noise mitigation systems for reducing pile-driving noise*. Inter-Noise Conference 2014, Melbourne, Australia.

Bjorge, A., & Tolley, K. A. (2008). Harbor porpoise *Phocoena phocoena*. In W. F. Perrin, B. Würsig, & J. G. M. Thewissen (Eds.), *Encyclopedia of marine mammals* (2nd ed., pp. 530-532). London: Academic Press.

Brandt, M. J., Diederichs, A., Betke, K., & Nehls, G. (2011). Responses of harbour porpoises to pile driving at the Horns Rev II offshore wind farm in the Danish North Sea. *Marine Ecological Progress Series*, *421*, 205-216. https://doi.org/10.3354/meps08888

Brandt, M. J., Höschle, C., Diederichs, A., Betke, K., Matuscheck, R., & Nehls, G. (2013a). Seal scarers as a tool to deter harbour porpoises from offshore construction sites. *Marine Ecological Progress Series*, *475*, 291-302. https://doi.org/10.3354/meps10100

Brandt, M. J., Höschle, C., Diederichs, A., Betke, K., Matuscheck, R., Witte, S., & Nehls, G. (2013b). Far-reaching effects of a seal scarer on harbour porpoises, *Phocoena phocoena*. *Aquatic Conservation: Marine and Freshwater Ecosystems*, *23*, 222-232. https://doi.org/10.1002/aqc.2311

Carstensen, J., Hendriksen, O. D., & Teilmann, J. (2006). Impacts of offshore wind farm construction on harbour porpoises: Acoustic monitoring of echolocation activity using porpoise detectors (T-PODs). *Marine Ecological Progress Series*, *321*, 295-308. https://doi.org/10.3354/meps321295

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

Gaskin, D. E., Smith, G. J. D., & Watson, A. P. (1975). Preliminary study of harbor porpoises (*Phocoena phocoena*) in the Bay of Fundy using radiotelemetry. *Canadian Journal of Zoology*, *53*, 1466-1471. https://doi.org/10.1139/z75-177

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

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

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

Kastelein, R. A., Hoek, L., de Jong, C. A. F., & Wensveen, P. J. (2010). The effect of signal duration on the underwater detection thresholds of a harbor porpoise (*Phocoena phocoena*) for single frequency-modulated tonal signals between 0.25 and160 kHz. *The Journal of the Acoustical Society of America*, *128*, 3211-3222. https://doi.org/10.1121/1.3493435

Kastelein, R. A., Hoek, L., Gransier, R., & de Jong, C. A. F. (2013a). Hearing thresholds of a harbor porpoise (*Phocoena phocoena*) for playbacks of multiple pile driving strike sounds. *The Journal of the Acoustical Society of America*, *134*, 2302-2306. https://doi.org/10.1121/1.4817889

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

Kastelein, R. A., Bunskoek, P., Hagedoorn, M., Au, W. W. L., & de Haan, D. (2002). Audiogram of a harbor porpoise (*Phocoena phocoena*) measured with narrow-band frequency-modulated signals. *The Journal of the Acoustical Society of America*, *112*, 334-344. https://doi.org/10.1121/1.1480835

Kastelein, R. A., Steen, N., de Jong, C., Wensveen, P. J., & Verboom, W. C. (2011). Effect of broadband-noise masking on the behavioral response of a harbor porpoise (*Phocoena phocoena*) to 1-s duration 6-7 kHz sonar up-sweeps. *The Journal of the Acoustical Society of America*, *129*, 2307-2315. https://doi.org/10.1121/1.3559679

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. *The Journal of the Acoustical Society of America*, *126*, 1588-1597. https://doi.org/10.1121/1.3177274

King, S. L., Schick, R. S., Donovan, C., Booth, C. G., Burgman, M., Thomas, L., & Harwood, J. (2015). An interim framework for assessing the population consequences of disturbance (C. Kurle, Ed.). *Methods in Ecology and Evolution*, *6*, 1150-1158. https://doi.org/10.1111/2041-210X.12411

Knudsen, V. O., Alford, R. S., & Emling, J. W. (1948). Underwater ambient noise. *Journal of Marine Research*, *7*, 410-429.

Linnenschmidt, M., Teilmann, J., Akamatsu, T., Dietz, R., & Miller, L. A. (2013). Biosonar, dive, and foraging activity of satellite tracked harbor porpoises (*Phocoena phocoena*). *Marine Mammal Science*, *29*, E77-E97. https://doi.org/10.1111/j.1748-7692.2012.00592.x

Nabe-Nielsen, J., Sibly, R. M., Tougaard, J., Teilmann, J., & Sveegaard, S. (2014). Effects of noise and by-catch on a Danish harbour porpoise population. *Ecological Modelling*, *272*, 242-251. https://doi.org/10.1016/j.ecolmodel.2013.09.025

National Marine Fisheries Service (NMFS). (2016). *Technical guidance for assessing the effects of anthropogenic sound on marine mammal hearing: Underwater acoustic thresholds for onset of permanent and temporary threshold shifts* (NOAA Technical Memorandum NMFS-OPR-55). Retrieved from www.nmfs.noaa.gov/pr/acoustics/Acoustic%20Guidance%20Files/opr-55_acoustic_guidance_tech_memo.pdf

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

Otani, S., Naito, Y., Kato, A., & Kawamura, A. (2000). Diving behaviour and swimming speed of a free-ranging harbor porpoise, *Phocoena phocoena*. *Marine Mammal Science*, *16*, 811-814. https://doi.org/10.1111/j.1748-7692.2000.tb00973.x

Otani, S., Naito, Y., Kato, A., & Kawamura, A. (2001). Oxygen consumption and swim speed of the harbor porpoise *Phocoena phocoena*. *Fisheries Science*, *67*, 894-898. https://doi.org/10.1046/j.1444-2906.2001.00338.x

Remmers, P., & Bellmann, M. A. (2016). *Offshore Wind Farm Gemini: Ecological monitoring of underwater noise during piling at Offshore Wind Farm Gemini* (Project Number 2571-15: OWF Gemini – Underwater Noise Measurements). 145 pp.

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

Zar, J. H. (1999). *Biostatistical analysis* (4th ed.). Upper Saddle River, NJ: Prentice Hall. 718 pp.