Agenda Item 3.5 — Implementation Review: Research

Investigation of the Effects of Anthropogenic Sounds on Harbour Porpoises (Action 11)

Information Document 3.5b — Effects of Multiple Exposures to Pile Driving Noise on Harbor Porpoise Hearing during Simulated Flights—An Evaluation Tool

Action Requested — Take note

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JASA ARTICLE

Effects of multiple exposures to pile driving noise on harbor porpoise hearing during simulated flights—An evaluation tool[a)]

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ABSTRACT:
Exploitation of renewable energy from offshore wind farms is substantially increasing worldwide. The majority of wind turbines are bottom mounted, causing high levels of impulsive noise during construction. To prevent temporary threshold shifts (TTS) in harbor porpoise hearing, single strike sound exposure levels (SEL_{SS}) are restricted in Germany by law to a maximum of 160 dB re 1 $\mu Pa^2 s$ at a distance of 750 m from the sound source. Underwater recordings of pile driving strikes, recorded during the construction of an offshore wind farm in the German North Sea, were analyzed. Using a simulation approach, it was tested whether a TTS can still be induced under current protective regulations by multiple exposures. The evaluation tool presented here can be easily adjusted for different sound propagation, acoustic signals, or species and enables one to calculate a minimum deterrence distance. Based on this simulation approach, only the combination of SEL_{SS} regulation, previous deterrence, and soft start allow harbor porpoises to avoid a TTS from multiple exposures. However, deterrence efficiency has to be monitored. https://doi.org/10.1121/10.0000595

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I. INTRODUCTION

The marine environment provides an almost infinite source of offshore renewables, which may be exploited with limited negative environmental impacts if guidelines are followed and the planning and scaling of projects are suitable (Pelc and Fujita, 2002). Increasing efforts have been made worldwide to exploit offshore renewables. In Germany, plans to refrain from extracting energy from fossil fuels or to close down nuclear power plants have been made over the last years and became even more ambitious after the disaster in 2011 at the nuclear power plant in Fukushima (Japan). Eighty percent of energy demands in Germany should be covered by renewable forms of energy by 2050. Since 2009 the German Federal Government's goal has been to reach 25 Gigawatt by 2030 from offshore wind capacity by undertaking intensive building of offshore wind farms (OWF) in German waters (BMWI, 2012). In total, 92 offshore wind farms have been constructed to date in eleven European countries including sites with partial grid connection, accounting for 4149 connected wind turbines (Remy and Mbistrova, 2018). This increased human encroachment overlaps with protected areas like the Sylt Outer Reef and could have negative effects on health, distribution, and behavior of key ecological species inhabiting German offshore areas.

The inconspicuous and only resident cetacean in the German North Sea is the harbor porpoise (*Phocoena phocoena*). It inhabits coastal waters and is therefore subject to anthropogenic pressures, e.g., accidental bycatch (ASCOBANS, 2002), continuous shipping noise (Bas *et al.*, 2017; Dyndo *et al.*, 2015; Wisniewska *et al.*, 2018), and impulsive noise from pile driving (Brandt *et al.*, 2018; Tougaard *et al.*, 2009), seismic surveys (Pirotta *et al.*, 2014), or underwater explosions (von Benda-Beckmann *et al.*, 2015). In European waters, harbor porpoises are protected among others within the framework of the Habitats Directive [listed in annexes II and IV (European Union, 1992)] and Council Regulation 812/2004 (European Union, 2004), implying that special areas should be established for their conservation with deliberate actions of killing, disturbing, injuring, and habitat deterioration being prohibited throughout its range (Council Directive 92/43/EEC, Article 12.1).

Although the prevention of injury in marine mammals has been considered globally (e.g., by the Habitats Directive in Europe or by the U.S. Marine Mammal Protection Act in the United States), injury is defined differently in national policies. According to the Federal Ministry for the Environment, Nature Conservation, and Nuclear Safety [BMU (2014)] in Germany, a temporary loss of hearing after exposure to pile driving noise [temporary threshold shifts (TTS)] is considered as an injury, whereas most other European countries or the United States regard a permanent hearing shift (PTS) as an injury. Lucke *et al.* (2009) derived data on TTS induced by single impulsive airgun stimuli, and defined an onset at a sound exposure level (SEL) of 164 dB re 1 μPa^2 s at a hearing frequency of 4 kHz, showing that harbor porpoises are more sensitive to impulsive noise than other high frequency cetaceans [reviewed in Southall *et al.* (2019)]. Consequently, the BMU published a regulation, which restricts the maximum SEL to 160 dB re 1 μPa^2 s for single impulsive noise at a

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distance of 750 m from the source (BMU, 2014) in reference to the findings of Lucke *et al.* (2009). To keep noise levels below this threshold, wind farm operators are obliged to use most innovative noise mitigation systems (NMS) like bubble curtains (Dähne *et al.*, 2017; Lucke *et al.*, 2011; Würsig *et al.*, 2000) and hydro sound dampers (HSD) (Elmer *et al.*, 2012). Additionally, acoustic deterrent devices (pinger and seal scarer) are deployed before pile driving, to deter animals from the area, where noise levels can exceed the threshold for an SEL of a single strike of 160 dB re 1 μPa^2 s.

Recent studies showed that besides the danger from a single pulse with high energy, the reception of multiple pile driving strikes with single strike sound exposure levels (SEL_{SS}) well below the legal threshold can also induce a TTS because of the total received energy. Indeed, playbacks of pile driving sounds at an SEL_{SS} of 146 dB re 1 μPa^2 s induced a TTS in harbor porpoises. A significant TTS at 4 and 8 kHz occurred after the playback of 2760 strikes within 60 min (Kastelein *et al.*, 2015a). A TTS_{onset} at 8 kHz hearing frequency was determined at a cumulative SEL (SEL_{cum}) of 175 dB re 1 μPa^2 s, corresponding to 1385 pile driving strikes of 145 dB re 1 μPa^2 s (SEL_{SS}) in 30 min (Kastelein *et al.*, 2016). Although regulations to protect harbor porpoises from TTS by single impulsive sounds have already been established, it was shown that the multiple reception of pile driving strikes can still induce a TTS.

In our present study, potential auditory hazard zones were estimated, within which hearing impairment is theoretically possible for harbor porpoises. Several behavioral scenarios were considered, which simulate effects for harbor porpoises that stay within the area of noise exposure and those that show a flight response at different literature-based swim speeds. The accumulation of sound energy from multiple pile driving strikes for harbor porpoises is determined by using real underwater recordings from recent pile driving activities in the German North Sea and its sound propagation. We estimated the potential to induce a TTS based on the distance to the pile driving site, and identified the minimum distance a harbor porpoise must be away from the pile driving site at the moment of the first strike to avoid auditory impairment.

The aim of this study is to provide a tool to evaluate effects of multiple pile driving events on harbor porpoise hearing. Equations presented here are adjustable for areas with differing sound propagation or further species with different TTS onsets, and allow the necessary minimum deterrent distances to be estimated. The outcomes of this study will highlight the efficiency of current protective measures in force in Germany to prevent temporary hearing shifts in harbor porpoises from pile driving noise. Currently, these measures restrict the maximum single strike exposure levels to 160 dB re 1 μPa^2 s at a distance of 750 m and the use of acoustic deterrent and harassment devices which are deployed before pile driving.

II. METHODS

A. Study site and pile driving recordings

Underwater recordings during the construction of 50 monopiles were conducted between August 27, 2014 and March 18, 2015 in order to determine underwater noise. Autonomous multichannel acoustic recorders (AMARs) (JASCO Applied Sciences, Canada) were bottom mounted at a depth of 20 m at seven measuring positions in the surrounding area of the German offshore Amrumbank West wind farm at distances between 2.4 and 36.8 km to pile driving sites (see Fig. 1 for further details on measuring positions and piles). Distances between measuring positions and pile driving sites could be determined by logging the position of measuring stations and reported pile positions by the wind farm operator. Background underwater noise was continuously recorded in 30 min files sampling at 32 ksamples s^{-1} and a 16-bit resolution. All AMAR recorders were equipped with

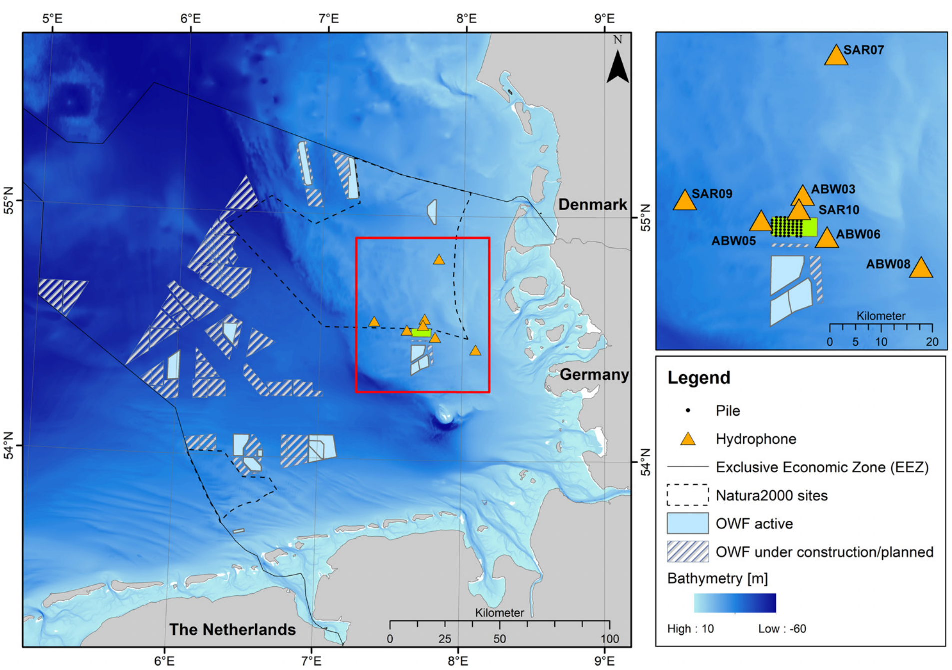

FIG. 1. (Color online) Research area in the German North Sea with marked positions of underwater recorders (triangle) and positions where pile-driving activities were conducted (points). Offshore wind farms (OWF), which are active to date, are marked as solid areas, while OWF, which are planned or under construction, are shown as dashed areas. Dashed lines represent FFH-protected areas (European Union, 1992). A zoom in on the research area (square) is shown in the top-right figure.

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omnidirectional GTI-M8E hydrophones (GeoSpectrum Technologies, Inc., Dartmouth, Canada) with nominal sensitivities of −160 and −200 dB re 1 V μPa^{-1}. In order to compensate for different received levels of pile driving strikes, less sensitive hydrophones were deployed at closer distances. The recording system was protected from bottom trawling by a trawl shield, meaning a glass fiber reinforced plastic housing (270 × 1250 × 1000 mm, H × W × D, 8 mm material thickness) built by DW-ShipConsult GmbH, Schwentinental Germany [see picture of trawl shield in Gerdes and Görler (2016), Fig. 3 (right picture)]. The trawl shield contained cropped circles on every side for a better sound transmission. The hydrophone was fixed inside the trawl shield below a cropped circle in a vertical position, pointing in the direction of the sea surface. External battery supplies were also employed inside the trawl shield to enable continuous recording over an approximately three-month period. The applied recording system fulfilled the requirements of ISO 18406 (2017) and the German guidelines (Müller and Zerbs, 2011) in terms of sampling frequency, data format, self-noise of the mooring system and electronic components, hydrophone sensitivity (<2 dB over the frequency range from 0.02 to 16 kHz) and interval of calibration (two years).

The investigated monopiles were deployed by two different wind farm installation vessels [MPI Discovery (Flag: the Netherlands) and HLV Svanen (Flag: the Bahamas)]. Further vessels applied big bubble curtains (BBC) and hydro sound dampers (HSD) for noise mitigation. Further information about the application of these NMS during the construction is not publicly accessible. Therefore, we cannot distinguish which NMS or combination of different NMS was utilized.

B. Sound propagation modeling and frequency analysis

Single strike sound exposure levels (SEL_{SS}) for the full frequency spectrum were calculated for each measuring position and constructed pile foundation in accordance with German measurement guidelines (Müller and Zerbs, 2011). All pile driving strikes, which were detected in the underwater noise recordings over the entire construction period, were analyzed. The median SEL_{SS} of all pile driving strikes per hour (SEL_{50} h^{-1}) was determined for each station and pile, describing the accumulated sound energy of these impulsive noise events related to 1 s and the reference pressure of 1 μPa (ISO 18406, 2017).

The sound propagation, based on the determined median SEL_{SS} per hour and distances to the pile driving site, was estimated by a non-linear regression. The intercept and the logarithmic regression factor were estimated by a non-linear least squares approach, using the nls function in R (R Core Team, 2019). Furthermore, we estimated the decay factor A in dB per meter within the nls approach. A weighting was applied to the model regarding the number of pile-driving strikes within the analyzed hour. The received level (RL) was estimated as

$$RL(R_K) = Intercept - slope \times log_{10}(Rk) - A(R_K), \quad (1)$$

where R_k is the distance to the pile-driving site, the intercept is the intercept of the regression, the slope is the slope of the regression, which is expected in the range of 10–20 and the decay factor A, which is a result from multiple reflections from the surface and seabed (Ainslie *et al.*, 2014; Lippert *et al.*, 2018; Martin and Barclay, 2019; Zampolli *et al.*, 2013). The estimated propagation parameters slope and A depend on the surface and bottom roughness, the sediment type and the speed profile within the water column. This sound propagation model was empirical based, but has to be considered as a broad estimate, because it does not consider any variations in bottom composition or bathymetry. Although sound propagation is much more complex and local variability may occur, this simple model enables a conceptual understanding of the propagation of pile-driving noise (Ainslie *et al.*, 2014; Lippert *et al.*, 2018; Martin and Barclay, 2019).

For comparative reasons, we also modeled a theoretical transmission loss (TL) over distance (R_k), which would be expected if guidelines are followed. The radiation characteristic of pile driving noise is considered to be more similar to a line than a point source, since the pile as a resonating body covers the entire water column in most of the cases. The proposed damped cylindrical spreading decay formula (Zampolli *et al.*, 2013) considers this sound propagation and has been shown to be applicable for pile-driving noise propagation within the North Sea up to a distance of approximately 15 km (Lippert *et al.*, 2018). Based on the current German regulation, we assumed an SEL_{SS} of 160 dB re 1 μPa^2 s at a distance of 750 m. The theoretical received level (RL) at the distance R_k was obtained from Eq. (1), under the assumption that pile-driving noise follows a damped cylindrical spreading, with R_k as the reference range of 750 m, where the SEL_{SS} is equal to 160 dB re 1 μPa^2 s. The decay factor was estimated by an empirical fit within a non-linear model, based on our empirical data of SEL_{50} h^{-1} over distance for data up to 15 km and the number of pile-driving strikes per hour as a weighting factor. Ambient noise was determined for a 30 s fraction of underwater sound recordings prior to pile-driving activities, when no pile-driving strikes occurred. Third octave spectra (2-base) were calculated for each 10 Hz high pass filtered 1 s window within the time window, for each pile at each measuring position for center frequencies ranging from 62.5 Hz to 12.7 kHz. In total, background recordings prior to six pile driving events at two measuring positions were analyzed, forming a database of eleven 30 s windows.

C. Model assumptions

The calculation of the potential hazard zone for auditory damages was based on several assumptions, which are described in the following.

A TTS_{onset} at 8 kHz hearing frequency was determined at a cumulative SEL (SEL_{cum}) of 175 dB re 1 μPa^2 s, corresponding to 1385 pile driving strikes of 145 dB re 1 μPa^2 s (SEL) in 30 min (Kastelein *et al.*, 2016).

Single events below a certain SEL_{SS} never induce a TTS or affect recovery and are therefore regarded as "effective quiet" (Finneran, 2015; Ward *et al.*, 1976). To date, no study has determined an effective quiet threshold for harbor porpoises but the best estimate can be derived from the lowest SEL_{SS} with the potential to induce a TTS, regardless of frequency or duration (Finneran, 2015). The lowest determined SEL_{SS} with the potential to induce a TTS was determined at 145 dB re 1 μPa^2 s (Kastelein *et al.*, 2016). In the absence of an empirically derived effective quiet threshold, we defined instead a threshold which is "still higher than effective quiet threshold" (SHEQ) as a proxy. A single strike sound exposure level of 145 dB re 1 μPa^2 s was defined as the SHEQ with the motivation to estimate a potential to cause a TTS by means of an SEL_{SS}, which proved to induce a TTS after multiple reception, instead of being conservative by considering all exposures. The implication of this is further discussed in chapter A of the discussion. Pile-driving strikes with SEL_{SS} below this SHEQ were therefore excluded from the calculation of cumulative received levels. The SHEQ was used in combination with the modeled sound propagation, to determine a "safe distance," where SEL_{SS} are below the SHEQ, and will not affect harbor porpoise hearing. The concept of the safe distance should be understood as a novel approach to estimate hazard zones instead of a fixed threshold. Further investigations are critically needed to determine an effective quiet threshold, in order to replace the SHEQ, which is currently suggested as the best guess.

Data on the swim speed of harbor porpoises are rare due to their inconspicuous lifestyle and poor accessibility. Only a few studies focused on the analysis of swim speed of harbor porpoises. Maximum swim speed for animals in human care were determined at 4.3 m s^{-1} (Otani *et al.*, 2001) and in the wild at 4.3 and 6.1 m s^{-1} (Gaskin *et al.*, 1974; Otani *et al.*, 2000). A maximum swim speed, derived from surfacing positions, was measured at 3.3 m s^{-1} for free-ranging animals (Brandt *et al.*, 2013; Linnenschmidt *et al.*, 2013). Mean swim speed of a free-ranging harbor porpoise was determined at 0.9 m s^{-1} (Otani *et al.*, 2000). An estimate of maximum swim speed endurance has not been published to date. Assumptions on swim speed are based on these available studies to cover a broad range of possible flight situations. Accordingly, harbor porpoise flights were simulated at a swim speed of 0.9, 3.3, 4.3, and 6.1 m s^{-1}.

We selected a pulse interval of 1.3 s which was used in the study by Kastelein *et al.* (2015a) and Kastelein *et al.* (2016), where the TTS_{onset} for multiple pile-driving strikes was taken from and which also fits well to the analyzed pile-driving events. We assumed equal source levels for all pile driving strikes and SEL_{SS} for a certain distance were treated as equal for the whole water column, since the acoustic field was measured from bottom-mounted sound recorders only. The implication of this is further discussed in Sec. IV A. All model assumptions are shown in Table I.

TABLE I. Summary of variables and values used for the model.

Variable	Assumption	Value
TTS_{onset}	SEL_{cum}	175 dB re 1 μPa^2 s
Effective quiet	SEL_{SS}	145 dB re 1 μPa^2 s
Safe distance	Distance where SEL_{SS} is below effective quiet	5604 m
Swim speed	Assumed to be constant	6.1, 4.3, 3.3, 0.9 m s^{-1}
Pulse interval	Time between pile driving strikes	1.3 s

D. Estimation of hazard zones

To estimate hazard zones, where a TTS can be induced by the reception of multiple pile driving strikes, we defined a "safe distance." At distances larger than the safe distance, SEL_{SS} are below the SHEQ (Finneran, 2015; Ward *et al.*, 1976) and will never induce a TTS or affect recovery, no matter how many signals will be received. A safe distance was determined using the slope, intercept, and decay factor of the modeled sound propagation.

The received cumulative sound exposure level was calculated as the sum of all received single strikes a harbor porpoise would receive on a simulated flight track, when swimming straight away from the sound source up to the determined safe distance. Harbor porpoise positions on the track were determined by steps with a length according to the given pulse interval of 1.3 s and the swim speed of the porpoise, straight away from the sound source. The pulse interval was derived from the analysis of underwater recordings. The expected porpoise position during the kth pile-driving strike, as a distance to the pile driving site (R_k) is thus

$$R_k = k_{pile\ strike} \times pulse\ interval \times swim\ speed + starting\ distance. \quad (2)$$

SEL_{SS} values were calculated as a function of distance to the pile driving position and the determined sound propagation for all simulated harbor porpoise positions on the flight track using Eq. (1).

The received SEL_{cum} for the entire flight from a simulated start position up to a distance, where SEL_{SS} is below the effective quiet threshold, can be obtained by

$$SEL_{cum} = 10 \times \log_{10} \sum_{k=1}^{n=total\ no.\ of\ strikes} \times 10^{(SEL_{SS_k}/10)} \left[dB\ re\ 1\ \mu\text{Pa}^2\ \text{s}\right]. \quad (3)$$

Based on the aforementioned equations we derived a closed-form solution for the received SEL_{cum} for a fleeing porpoise (see Sec. III). We verified this analytical solution by simulating fleeing porpoises in which we iteratively summed up received levels of single strikes. All analyses were performed and figures created using R (R Core Team, 2019).

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III. RESULTS

A. Sound propagation in the study area

A total of 912 820 pile-driving strikes were detected and analyzed in recordings with pile driving activity. Inter-pulse intervals varied between 0.8 and 2.2 s. The most distinct inter-pulse interval was found at 1.0 s, followed by 1.6 s (Ruser *et al.*, 2016), indicating that the fixed inter-pulse interval in the simulation approach of 1.3 s was representative for actual pile driving activities. Energy spectra of 76 448 pile driving strikes from six monopiles at two measuring positions were further analyzed. Most of the energy was found to be below 2 kHz with a peak around 160 Hz (Fig. 2). A further lower peak for frequencies around 5 kHz was also found for some piles (ABW48, ABW59 in Fig. 2).

Received levels of single strikes (SEL_{SS}) ranged from 101.9 to 165.2 dB re 1 μPa^2 s at distances between 2.4 and 36.8 km (see Fig. 3). The received level (RL) was estimated by a non-linear logarithmic regression, estimating the intercept, slope and decay factor A in dB per meter based on the determined median SEL_{SS} per hour. We found

$$RL(R_k) = 200.5 - 13.64 \times \log_{10}(R_k) + 0.00078\,(R_k)\ \left[\text{dB } re\ 1\ \mu\text{Pa}^2\ \text{s}\right] \quad (4)$$

as the best fit for the analyzed pile driving strikes over distance. The modeled sound propagation is shown in Fig. 3 as a solid line. We used the number of pile-driving strikes as a weighting factor for the model. A median of 772

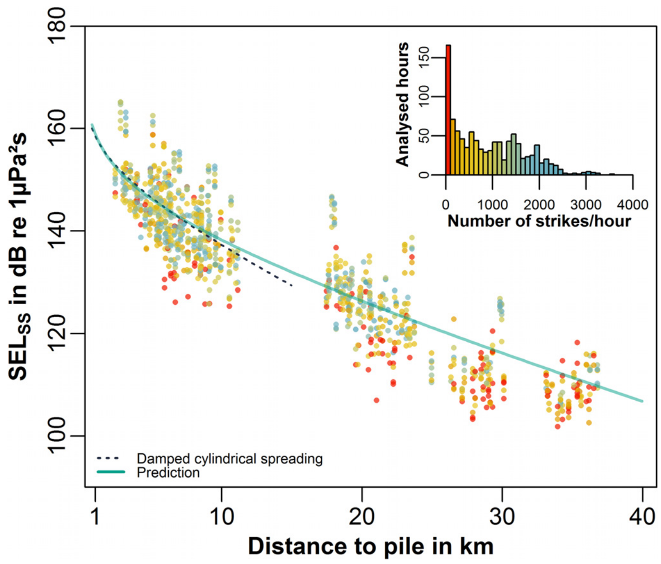

FIG. 3. (Color online) Determined SEL_{SS} in dB (re 1 μPa^2 s) of pile-driving activities during the construction of 50 monopiles in the Amrumbank West OWF. Sound recordings were conducted at seven static measuring positions. The median SEL_{SS} of all detected strikes per hour is marked by points. Sound propagation was modeled by a non-linear regression (solid line), estimating the intercept (200.5), slope (−13.64), and decay factor A (0.00078). The theoretical sound propagation, assuming a damped cylindrical spreading with a received level of 160 dB re 1 μPa^2 s at a distance of 750 m is presented by the dashed line. The empirical based best fit for the decay factor A was estimated at 0.0012 dB per meter, which is in line with the empirical derived decay factors reported by Lippert *et al.* (2018) The number of strikes within an hour is shown by color-coded points and its distribution is shown in the histogram in the top right corner.

pile-driving strikes per hour was found (sd = 753, range 1–3586). The SEL_{SS} at a distance of 750 m was estimated at 160.8 dB re 1 μPa^2 s.The number of strikes within an hour is shown by color-coded points and its distribution is shown in the histogram in the top right corner (Fig. 3).

The theoretical sound propagation, assuming a damped cylindrical spreading with a received level of 160 dB re 1 μPa^2 s at a distance of 750 m is presented by the dashed line. The best fit for the decay factor A was estimated at 0.0012 dB per meter, which is in line with the empirical derived decay factors reported by Lippert *et al.* (2018). For distances up to 10 km the predicted sound propagation and the theoretical sound propagation (Lippert *et al.*, 2018; Zampolli *et al.*, 2013) showed high similarity. The theoretical sound propagation is not reliable for distances further than 15 km.

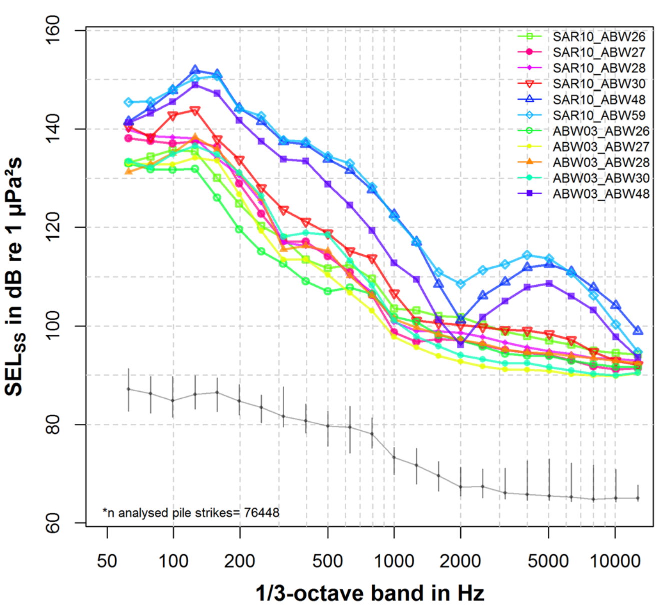

FIG. 2. (Color online) Third octave level spectrum of the analyzed pile driving events, color- and symbol-coded for measuring position and pile. Each mark on the line represents the determined median SEL_{SS} for the corresponding center frequency of the third octave band. The median ambient noise level of all analyzed 30 s recordings prior to pile-driving activities is shown as the lowest line with vertical lines representing the 1.5 interquartile range. The distances to the pile-driving site can be found in the Appendix.

B. Estimation of hazard zones

The calculation of the potential hazard zone for auditory damages was based on several assumptions, which are described in Sec. II.

The potential to induce a TTS in harbor porpoises, which do not show a flight response, was presented by showing the maximum radius where a TTS can be induced from multiple pile-driving strikes above the SHEQ. The hazard radius corresponds therefore to the determined safe distance using the slope, intercept and attenuation factor of the modeled sound propagation along with the effective quiet threshold. Therefore, we re-arranged Eq. (4) in order to calculate a safe distance with a given received level, corresponding to the effective quiet threshold. The rearrangement required the usage of the Lambert *W* function (Corless *et al.*, 1996) to solve the equation in which the unknown distance appears both outside and inside a logarithmic function, leading to

$$safe\,distance = \frac{-\left\{slope \times W\left[\frac{-10^{(-intercept+eqt)/slope} \times A \times \ln(10)}{slope}\right]\right\}}{A \times \ln(10)}\ [\mathrm{m}]. \tag{5}$$

To calculate the safe distance, defined as a distance where the single strike level is 145 dB re 1 μPa^2 s, we inserted the intercept (200.5 dB), slope (−13.64 dB) and the attenuation factor A (0.00078 dB m^{-1}) of the determined logarithmic regression of the received levels into this equation. The safe distance was determined at 5604 m.

According to an assumed pulse interval of 1.3 s, the $\mathrm{SEL_{cum}}$ would exceed the $\mathrm{TTS_{onset}}$ of 175 dB re 1 μPa^2 s in 21.7 min within the area up to the safe distance. Animals located within the area up to the determined safe distance at 5.6 km are estimated to suffer from a TTS within a maximum of 21.7 min.

By a simulation approach, we determined the minimum distance a harbor porpoise must be deterred prior to pile-driving activities, to escape hearing impairment by a continuous flight up to the assumed safe distance. Therefore, we modeled the total received $\mathrm{SEL_{cum}}$ for a complete flight track from various start positions up to the safe distance at which the received $\mathrm{SEL_{SS}}$ was below 145 dB re 1 μPa^2 s (SHEQ). Results were obtained for all possible start positions ranging from zero to the safe distance. This simulation was conducted using the variables and their specified values presented in Table I.

Thus, the received $\mathrm{SEL_{cum}}$ for the entire track of a harbor porpoise swimming straight away from the sound source from an assumed position (start distance) up to the safe distance (determined at 5604 m) can be obtained by

$$SEL_{cum} = 10 \times \log\left\{\frac{10^{intercept/10}}{pulse \times speed} \times \frac{A \times \ln(10)}{10}^{slope/10-1} \times \left[\Gamma\left(1-\frac{slope}{10}, \frac{A \times \ln(10) \times dist.start_k}{10}\right) - \Gamma\left(1-\frac{slope}{10}, \frac{A \times \ln(10) \times \mathrm{safe\,distance}}{10}\right)\right]\right\} \times [\mathrm{dB}\ re\ 1\ \mu\mathrm{Pa}^2\mathrm{s}]. \tag{6}$$

For the received $\mathrm{SEL_{cum}}$ we find for $\Gamma(a,x) = \int_x^\infty t^{a-1} e^{-t}\,dt$ as the upper incomplete gamma function, giving an estimate for any transmission loss factor (slope) between cylindrical ($10 \times \log_{10}$) and spherical ($20 \times \log_{10}$) spreading. To integrate the decay factor A, the incomplete gamma function had to be included, which arises as a solution for certain integrals. We calculated the received $\mathrm{SEL_{cum}}$ for all tested swim speeds with varying start distances ($\mathrm{dist.start_k}$) ranging from 750 m up to the safe distance with Eq. (6) (see the R-script in the Appendix).

Afterwards, we determined the minimum distance at which the $\mathrm{TTS_{onset}}$ of 175 dB re 1 μPa^2 s (Kastelein *et al.*, 2016) was not exceeded. This distance was defined as the minimum distance a harbor porpoise must be away from the pile-driving site at the moment of the first strike to reach the safe distance by a continuous flight before the cumulative energy can induce a TTS. This distance was called the minimum deterrence distance.

Minimum deterrence distances are shown in Table II for simulated harbor porpoises swimming away at four different speed levels. Assuming an immediate flight with 6.1 m s^{-1} after the first pile-driving strike, harbor porpoises have to be further away than 2399 m from the construction site to successfully prevent a TTS (Fig. 4, Table II). A harbor porpoise starting a flight at a distance of 2432 m with a constant speed of 6.1 m s^{-1} can still receive cumulative sound energy exceeding the $\mathrm{TTS_{onset}}$ after 8.8 min of a continuous flight and the reception of 405 pile driving strikes in that period. Harbor porpoises, which are capable of fleeing at a speed of 4.3 m s^{-1}, have to be more than 2897 m away from the construction site to reach the safe distance before the received $\mathrm{SEL_{cum}}$ exceeds the $\mathrm{TTS_{onset}}$. Slowly

TABLE II. Simulation results for the maximum distance as a start position for a flight, where a TTS could still be induced before reaching the safe distance. Moreover, the number of received pile-driving strikes on the track from the minimum deterrence distance up to the safe distance are given as same as the time of traveling in minutes. Simulation results are presented for four swim speed levels.

Swim speed in ms^{-1}	Min. deterrence in m	Strikes to safe distance	Travel time to safe distance in min
0.9	4659	807	17.5
3.3	3255	547	11.9
4.3	2897	484	10.5
6.1	2399	404	8.8

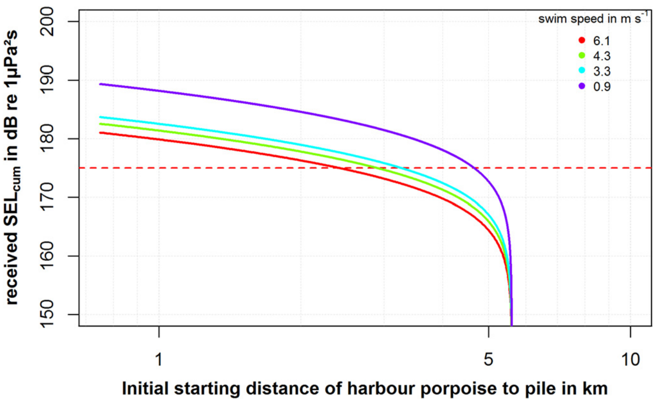

FIG. 4. (Color online) Simulation harbor porpoise fleeing from a certain start position (*x* axis) up to the safe distance (5604 m). The received SEL_{cum} for the complete flight track (*y* axis) is color-coded for each tested swim speed. The horizontal dashed line at 175 dB re 1 μPa^2 s indicates the assumed TTS_{onset}.

swimming harbor porpoises, traveling at a speed of 0.9 m s^{-1} can still suffer from a TTS when starting a flight at the beginning of pile driving activities at a distance of 4659 m. Within 17.5 min, a harbor porpoise fleeing at 0.9 m s^{-1} could receive a cumulative SEL exceeding the TTS_{onset} after 808 strikes before reaching the safe distance.

Single pile-driving strikes are limited by legislation to a maximum of 160 dB re 1 μPa^2 s at a distance of 750 m in Germany (Fig. 5, green circle). Underwater recordings revealed that up to a distance of 5604 m, SEL_{SS} are high enough, to induce a TTS by multiple exposures (Fig. 5 red circle). We could show by means of a simulation that even harbor porpoises fleeing at a constant speed of 6.1 m s^{-1} have to be deterred 2.4 km prior to the first pile-driving strike to successfully reach the safe distance before the TTS_{onset} is exceeded by multiple exposures and a TTS is likely.

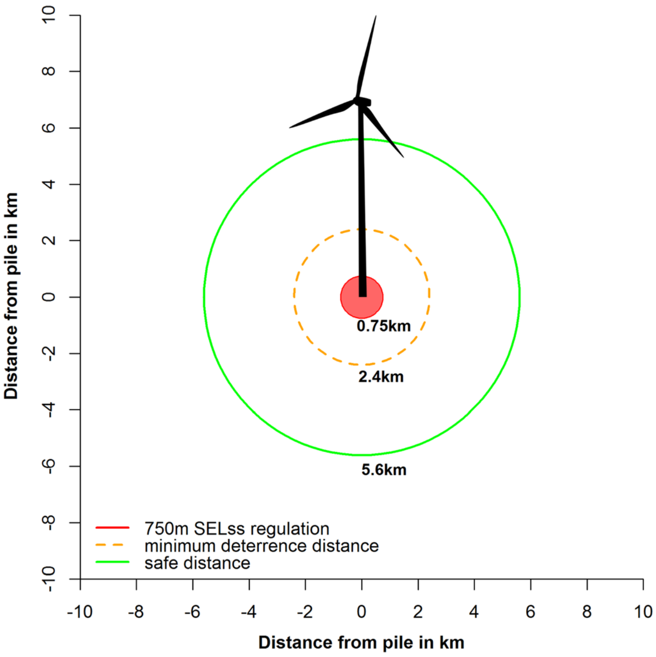

FIG. 5. (Color online) Radii of hazard zones around a pile-driving site, where the TTS_{onset} of 175 dB re 1 μPa^2 s can be exceeded by multiple events above the SHEQ of 145 dB re 1 μPa^2 s for single strikes. A TTS could be induced in harbor porpoises within 21.7 min at a distance up to 5.6 km, if animals stayed within (outer circle). Harbor porpoises closer than 2.4 km could still suffer from a TTS, even if fleeing immediately after the 1st pile driving strike with a swim speed of 6.1 m s^{-1} (dashed middle circle). The distance of 750 m, where SEL_{SS} were restricted to 160 dB re 1 μPa^2 s as a protective measure, is shown as the inner circle.

IV. DISCUSSION

In this study, underwater sound recordings of real pile-driving events were used in combination with modeled sound propagation, swim speed, and pulse intervals to estimate potential TTS hazard zones for harbor porpoises. The transmission loss is strongly dependent on site-specific parameters like frequency of sound, water temperature, salinity, depth, acidity, bottom type, and sea state (Marsh and Schulkin, 1962) and can often, even for single paths, not be extrapolated to larger distances (Madsen *et al.*, 2006). While the analysis of 912 820 analyzed pile-driving strikes enabled us to model an accurate sound propagation within the research area, the extrapolation of the results of this study to other areas should be made with great caution. Source levels of pile-driving strikes, applied noise mitigation systems and numerous physical parameters of the acoustic field influence the sound propagation and frequency spectra of these strikes, which are the driving factors for predicting potential hazard zones. We present a comprehensive but also parsimonious model, which can easily be adjusted to other areas with different sound propagation conditions or integrating updated variables.

As a novel approach, we considered an effective quiet threshold to classify areas where a TTS can be induced by multiple exposures. Since we assume the same pulse interval and only consider SEL_{SS} above the playbacks used in the study by Kastelein *et al.* (2016), we are confident that the TTS_{onset} is reliable or could be even lower when exposed to SEL_{SS} of higher energy. Our simulation approach is, however, limited for predictions with pulse intervals, which are higher than the assumed 1.3 s. The assumption that equal cumulative energy induces an equal hearing shift is only valid for continuous fatiguing noises or for exposures with similar duty cycles (e.g., Finneran *et al.*, 2010a, 2010b, Kastelein *et al.*, 2015b, 2014; Mooney *et al.*, 2009; Popov *et al.*, 2014). Based on the analysis of underwater recordings from 50 monopiles over a range from 2.4 and 36.8 km, we could show that noise levels are high enough to induce a TTS by multiple exposures up to a distance of 5604 m.

A. Simulation results

In contrast to direct effects on hearing, behavioral reactions of free-ranging harbor porpoises to pile-driving strikes are not fully understood yet. Tagging of harbor porpoises with high resolution sound and movement recording tags [DTAG, Johnson *et al.* (2009)] allows for detailed analysis of behavioral and physiological reactions on an individual basis. Tag-based studies could show that vessel noise evokes clear behavioral responses in harbor porpoises, coinciding with deeper dives, disturbance of foraging, increased fluke strike rates and cessation of echolocation (Wisniewska *et al.*, 2018). Since we do not know how harbor porpoises could react to pile-driving noise, we simulated two different scenarios from the perspective of a wild harbor porpoise exposed to pile-driving noise: However, future research is needed to ascertain their feasibility.

If the porpoise did not show a flight response and stayed inside the area where the noise levels are high enough to induce a TTS by multiple exposures up to a distance of 5604 m, the received SEL_{cum} would exceed the TTS_{onset} anywhere within this area after 21.7 min at a pulse rate of 1.3 s at the latest. Ecological reasons for staying within hazardous areas could be due to strong inter-individual variability with animals not responding to that disturbance or tolerating the noise if staying in an area is beneficial, for instance, because of high quality food. Staying within a hazardous area could be either a result of natural decision-making or also caused by a lack of information in which direction to swim. Sound source localization ability of harbor porpoises has been found to be better for longer signals but has been tested for frequencies above 16 kHz only (Kastelein *et al.*, 2007). It has not been described whether harbor porpoises are capable of localizing sound sources at such low frequencies and short duration like pile-driving strikes. The spectral content of sounds determines the ability to localize its origin (Branstetter and Mercado III, 2006; Kastelein *et al.*, 2005). Therefore, it is reasonable to assume that localizing signals with higher frequency content is easier for harbor porpoises, like shown for harbor seals, which are also underwater hearing specialists (Bodson *et al.*, 2007). Consequently, mitigated pile-driving strikes could be even harder to localize, because bubble curtains are more effective in mitigating frequency content above 1 kHz (Dähne *et al.*, 2017, Fig. 3).

In order to estimate potential hazard zones for harbor porpoises, which immediately flee after the first pile-driving event, we simulated the received SEL_{cum} for a complete flight track up to the safe distance. We wanted to determine a minimum distance by this approach, a harbor porpoise must be deterred prior to pile-driving activities for in order to prevent a TTS, before the TTS_{onset} is exceeded. We could demonstrate that a harbor porpoise, which is within a radius of 2.4 km to the pile-driving site, cannot reach the safe distance before the TTS_{onset} is exceeded by the reception of multiple strikes. The simulated fleeing harbor porpoise received pile-driving strikes from behind. Although hearing in harbor porpoises is directional with better abilities for signals ahead (Kastelein *et al.*, 2005), our simulation is assumed to be valid. The receiving beam of harbor porpoises is wider for lower frequencies (Kastelein *et al.*, 2005) and the TTS_{onset} was derived from a study where harbor porpoises were exposed from varying positions while swimming freely in a pool (Kastelein *et al.*, 2015a,b; Kastelein *et al.*, 2016). Our simulation approach cumulates multiple received pile-driving strikes, which are equal to or higher than the SEL_{SS} used in a playback experiment with animals in human care, in which a TTS_{onset} was determined at 175 dB re 1 μPa^2 s (Kastelein *et al.*, 2016). Within that playback study, SEL_{SS} were the same throughout the whole exposure. A fleeing harbor porpoise would, however, receive pile-driving strikes with decreasing SEL_{SS} with increasing distance to the sound source. In contrast to Kastelein *et al.* (2016), the harbor porpoise would receive multiple strikes with variable SEL_{SS}, which are all above the SEL_{SS} in that playback experiment. It is reasonable to assume that this could lead to a lower TTS_{onset}, because the TTS_{onset} is dependent on the duty cycle, sound pressure level (SPL) and received SEL_{cum} (Kastelein *et al.*, 2015b, 2014). However, a TTS_{onset} for varying or decreasing SEL_{SS} over time has not been determined yet.

Although effects of pile-driving noise on harbor porpoise sightings and acoustic detections have been described (Brandt *et al.*, 2018; Dähne *et al.*, 2013), behavioral reactions of harbor porpoises regarding swim speed, echolocation behavior, diving depth, and duration remain unknown to date. In order to protect its hearing, harbor porpoises could flee close to the surface or bottom, to benefit from interferences, mitigating received SEL_{SS} by reflections (Lloyd mirror effect). This could be the case for described reactions of a harbor porpoise towards high levels of vessel noise, which remained close to the bottom during highest levels of exposure (Wisniewska *et al.*, 2018). The actual swimming depth of harbor porpoises within the hazard area can highly change the received exposure level, which accordingly affects estimated hazard zones. The modeled sound propagation has been derived from recordings of bottom mounted underwater sound recorders, limiting the validity for predictions for the entire water column. There are only few data available for the variability of received levels of pile driving strikes in the water column. Received levels of pile-driving strikes at distances between 3.8 and 14.6 km from the pile-driving source showed a depth dependency with a variability of up to 5.8 dB between received levels at 1 and 13 m from the bottom [total depth 23 m, Gerdes *et al.* (2016)]. The received levels were highest at the bottom, decreased with distance to the surface and displayed also a slight tendency for the level difference to decrease with increasing distance to the pile (Gerdes *et al.*, 2016). However, this limitation within the simulation approach has to be reconsidered if more information on harbor porpoise reactions to pile-driving noise is reported.

B. Application of evaluation tool

This study presents a novel approach to evaluating the impact of anthropogenic impulsive noise on harbor porpoise hearing, by considering a distance where noise exposure does not affect hearing anymore. Equation (6) can be applied to calculate the received cumulative SEL on a flight up to the safe distance, and can be easily adjusted to different sound propagation measurements. Furthermore, frequency weighting functions can be easily applied to the

TTS_{onset} and the effective quiet threshold, if perceived loudness proves to be the best predictor for auditory impairment (Houser *et al.*, 2017; Kastelein *et al.*, 2017; Southall *et al.*, 2019; Tougaard and Dähne, 2017). All presented simulations involve simplifications and assumptions leading to non-negligible uncertainty in the estimated hazard zones.

As an example, we applied the formula to estimate hazard zones on reported SEL_{SS} of further offshore wind farms in the German North Sea. Based on underwater recordings during the construction of seven offshore wind farms in the German North Sea, average SEL_{SS} of 168 dB re 1 μPa^2 s could be determined for noise mitigated pile-driving events at a distance of 750 m (Brandt *et al.*, 2018). The SEL_{SS} of unmitigated pile-driving strikes at a distance of 750 m was determined at 175 dB re 1 μPa^2 s in the same study. The sound propagation determined by Brandt *et al.* (2018) was very similar to the sound propagation modeled in this study. Using the SEL_{SS} results of Brandt *et al.* (2018) for mitigated pile-driving strikes and assuming the same sound propagation as in this study, the safe distance would be at 10.4 km. The minimum deterrence distance, derived from our simulation approach, would be between 6.6 and 9.4 km for noise mitigated pile-driving events, depending on swim speed. The safe distance for unmitigated pile-driving strikes would be at 15.8 km and minimum needed deterrent distances ranged between 11.7 and 14.8 km, depending on swim speed. A clear deterrence effect was found for SEL_{SS} above 143 dB re 1 μPa^2 s, reaching up to distances of 17 km (Brandt *et al.*, 2018). These findings are in line with the determined threshold at which harbor porpoises in human care began to respond to pile-driving playbacks with porpoising behavior (Kastelein *et al.*, 2013). These behavioral thresholds of about 145 dB re 1 μPa^2 s correspond to the assumed SHEQ, which determines the safe distance and the lowest level of single strikes, which were taken into account. The safe distance was determined at 15.8 km, whereas the deterrence range was measurable up to 17 km (Brandt *et al.*, 2018). Due to a high similarity in results, we assume that the evaluation tool allows for a reliable prediction of potential hazard zones where a temporary threshold shift can be induced by multiple pile-driving strikes.

Although attempts are made to protect marine mammals from injuries worldwide, national policies disagree in the definition of injury. While Germany considers a temporary threshold shift as an injury, most other states define injury in the context of hearing as a permanent threshold shift (e.g., U.S. Marine Mammal Protection Act in the United States). Recently, updated noise exposure criteria have been proposed to predict the onset of auditory effects in marine mammals (Southall *et al.*, 2019). The SEL onsets are presented as weighted levels, accounting for the frequency dependent effects in order to better meet perceived loudness of the animal. The harbor porpoise belongs to the group of the very high frequency cetaceans (VHF) in the recommended marine mammal noise exposure criteria (Southall *et al.*, 2019). The weighted onset was determined at 155 dB re 1 μPa^2 s for PTS and at 140 dB re 1 μPa^2 s for TTS. In order to adopt these suggested PTS- and TTS_{onset} thresholds in our simulation approach, the SHEQ also has to be adjusted to the frequency weighting. The SHEQ is based on the playback study by Kastelein *et al.* (2016), which were found to be 40 dB lower with applied frequency weighting (Tougaard and Dähne, 2017, Table I). Accordingly, the weighted threshold was also decreased by 40 dB, down to 105 dB re 1 μPa^2 s.

Within the analysis of pile driving recordings in this study, frequency weighting was not included in the project scope. Alternatively, published acoustic properties of pile-driving strikes recorded in the offshore DanTysk windfarm can be consulted (Dähne *et al.*, 2017) to estimate the potential to induce a PTS or TTS for a frequency-weighted sound propagation. A frequency-weighted source level of 170 dB re 1 μPa^2 s was estimated from pile-driving activities of 80 piles, measured at distances between 1 and 31 km, by fitting a simple transmission loss model with $15 \times \log 10(R)$ and no absorption (Dähne *et al.*, 2017). Accordingly, the calculated safe distance extends to 21.5 km for this data-set, consisting of unmitigated, single- and double-bubble curtain-mitigated strikes. To escape a PTS, a minimum deterrence distance between 57 and 1155 m (Table III) would be needed for swim speeds between 6.1 and 0.9 ms^{-1}, following the criteria of Southall *et al.* (2019). The hazard zone where a PTS can be induced for fleeing harbor porpoises extends to 1.2 km in the worst case scenario with a swim speed of 0.9 ms^{-1}. Regarding the reported effectiveness of previous deterrence (Brandt *et al.*, 2012, 2013), a PTS is assumed to be negligible. To escape a TTS with the same assumptions, a minimum deterrence distance of between 4.5 and 7.6 km would be needed (Table III). However, the minimum deterrence distances for weighted pile-driving strikes from DanTysk are larger (2.3 and 6.5 km, Table III), compared to the unweighted results presented in this study. Nevertheless, these also compare to the unweighted strikes reported in (Dähne *et al.*, 2017). These differences in potential hazard zones emphasize the need for a standardized risk evaluation.

C. Ecological relevance of disturbance

The TTS_{onset} derives from a study, which determined a statistically significant TTS after multiple exposure to pile-driving playbacks, which was small and could only be measured due to quiet experimental pools and low variability (Kastelein *et al.*, 2016). However, a statistically significant TTS does not inevitably mean it is ecologically significant. To date, it is still unknown what the ecological effects of TTS are. Nevertheless, it is assumed that these are related to the duration, affected frequency range and magnitude (Kastelein *et al.*, 2017). Potential consequences could be reflected in difficulties to hear in noisy environments. The acoustical perception of the environment is of key importance for harbor porpoises when navigating (Villadsgaard *et al.*, 2007), finding and catching prey (DeRuiter *et al.*, 2009; Wisniewska *et al.*, 2016) and for intra-specific

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TABLE III. Application example of simulation approach, using the acoustic properties of pile-driving strikes reported by Dähne *et al.* (2017). The minimum deterrence for fleeing harbor porpoises is simulated for the reported sound propagation of pile driving-strikes from the construction work of the offshore windfarm DanTysk by using of the recommended noise exposure criteria of Southall *et al.* (2019) and compared to the unweighted threshold of Kastelein *et al.* (2016). The simulation results for the maximum distance as a start position for a flight, where a TTS could still be induced before reaching the safe distance, are presented for the potential to cause a PTS and TTS and for four swim speed levels each.

Injury criteria	Onset in dB re 1 μPa^2 s	Weighting function	Swim speed in ms^{-1}	Min. deterrence in m
PTS, Southall *et al.* (2019)	155 (PTS)	$NOAA_{HF}$ weighted	0.9	1155
PTS, Southall *et al.* (2019)	155 (PTS)	$NOAA_{HF}$ weighted	3.3	160
PTS, Southall *et al.* (2019)	155 (PTS)	$NOAA_{HF}$ weighted	4.3	102
PTS, Southall *et al.* (2019)	155 (PTS)	$NOAA_{HF}$ weighted	6.1	57
TTS, Southall *et al.* (2019)	140 (TTS)	$NOAA_{HF}$ weighted	0.9	7548
TTS, Southall *et al.* (2019)	140 (TTS)	$NOAA_{HF}$ weighted	3.3	5853
TTS, Southall *et al.* (2019)	140 (TTS)	$NOAA_{HF}$ weighted	4.3	5312
TTS, Southall *et al.* (2019)	140 (TTS)	$NOAA_{HF}$ weighted	6.1	4513
TTS, Kastelein *et al.* (2016)	175 (TTS)	Unweighted	0.9	6509
TTS, Southall *et al.* (2019)	175 (TTS)	Unweighted	3.3	3759
TTS, Southall *et al.* (2019)	175 (TTS)	Unweighted	4.3	3104
TTS, Southall *et al.* (2019)	175 (TTS)	Unweighted	6.1	2293

communication (Clausen *et al.*, 2010; Sørensen *et al.*, 2018) and any impairment could potentially negatively affect individual fitness, reproduction, or survival. Anthropogenic noise does not inevitably lead to individual mortality but can affect the behavior of individuals causing sublethal effects (Pirotta *et al.*, 2015). Noise exposure can also lead to indirect mortality caused by stress responses, affecting physiology (Aguilar de Soto *et al.*, 2016; Wright *et al.*, 2007). Effects can occur in various forms and can therefore be interacting or cumulative (Kunc *et al.*, 2016).

The here tested maximum swim speed of 6.1 m s^{-1} (Gaskin *et al.*, 1974) probably overestimates the average speed of harbor porpoises, determined as being between 0.7 and 2.2 m s^{-1} (Linnenschmidt *et al.*, 2013; Otani *et al.*, 2000) or between 1.3 and 3.2 m s^{-1} during flight responses to seal scarer signals (Brandt *et al.*, 2013). Harbor porpoises in human care were capable of maintaining an increased swim speed of 2 m s^{-1} throughout 30 min, when exposed to pile-driving playbacks with an SEL_{SS} of 145 dB re 1 μPa^2 s (Kastelein *et al.*, 2018). The extent to which swim speed levels increase in wild animals is essential for predicting energetic costs. The resulting drag from moving in a medium increases with the square of swim speed and likewise the needed costs of locomotion for propulsion against the drag (Gallagher *et al.*, 2018; van der Hoop *et al.*, 2014). Harbor porpoises live on an energetic knife edge, which makes them particularly vulnerable to anthropogenic disturbance (Wisniewska *et al.*, 2016). Therefore, every extra needed food intake due to increased energetic costs and missed time for foraging during a disturbance could have a severe impact.

Although there is no common EU regulation concerning noise mitigation during the construction of offshore wind farms, wind farm industries are obliged in several European countries to actively mitigate noise emission (Belgium, Denmark, Germany, and the Netherlands) or to restrict piling activities to designated time periods (Belgium and the Netherlands). German legislation has enforced strictest regulations in the EU to date, by determining a maximum single strike SEL of 160 dB re 1 μPa^2 s and a maximum SPL of 190 dB re 1 μPa at a distance of 750 m, obligatory deterrence of harbor porpoises prior to piling activities and using a soft start procedure with limited force and longer pulse intervals. Our analysis of the recorded pile driving strikes show that the protective measure of restricting SEL_{SS} to 160 dB re 1 μPa^2 s in 750 m, in order to protect harbor porpoises from TTS by single strikes, was respected. Additionally, this measure is very effective in reducing the potential hazard zones, where a TTS can be induced by multiple exposures. We could show that deterrence of at least 2.4 km prior to pile-driving strikes is necessary to allow a flight of harbor porpoises up to the safe distance before the TTS_{onset} is exceeded. In order to deter harbor porpoises, seal scarers are deployed prior to piling activities. The effective deterrence range of a commercial seal scarer (Lofitech, Leknes, Norway) was measured as being 1.9 km by visually observing surfacing positions (Brandt *et al.*, 2013). The available data within the piling protocols concerning the soft start was incomplete. Neither the duration of the soft start nor the pulse interval or used strike energy is regulated in Germany. In combination with the soft start in the beginning of pile-driving activities with restricted force and longer pulse intervals, this previous deterrence could be sufficient to allow for a continuous flight up to the safe distance at 5604 m before TTS_{onset} is exceeded. However, effectiveness of deterrence effort has to be monitored if all harbor porpoises should be protected. Only combining noise mitigation and deterrence efforts within current regulations in Germany could be sufficient to enable harbor porpoises to flee in time, but this has to be monitored for effectiveness. Deterrence should be great enough prior to pile-driving activities (minimum deterrence distance) to give harbor porpoises sufficient time to flee to areas where no TTS can be induced. However, on the other hand, it has to be as low as possible, to reduce temporary habitat loss.

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D. Conclusion

Our approach to evaluating the potential for causing a TTS from multiple pile driving events can be easily adjusted to different areas with other sound propagation characteristics. Furthermore, it can be adjusted for other sound signals or species with different TTS_{onsets} or for an updated TTS_{onset} if further studies are conducted, using variable SEL_{SS}, for example. Our simulations show that implemented measures during the construction of OWF in Germany represent a valuable tool for protecting harbor porpoises not only from single but also from multiple pile-driving strikes. The deterrence prior to pile-driving events is particularly important and has to be monitored to give harbor porpoises sufficient time to leave hazardous areas at moderate speeds. Based on our simulation approach, only the combination of restricting the maximum SEL_{SS} to 160 dB re 1 μPa^2 s at a distance of 750 m, a previous deterrence and a soft start with reduced energy and longer pulse intervals allow harbor porpoises to avoid a TTS from multiple exposures. However, deterrence efficiency has to be monitored.

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APPENDIX: R COMMANDS TO CALCULATE THE SAFE DISTANCE AND RECEIVED SEL_{CUM} ON FLIGHT TRACK

```
# Define base parameters
sheq <- 145 # effective quiet threshold
pulse <- 1.3 # interpulse interval
TTS_onset <- 175 # TTS onset for multiple exposure with pile-driving strikes
slope <- -13.64 # slope of regression
intercept <- 200.5 # intercept of regression, estimated SL
A <- 0.00078 # attenuation factor, absorption integrated
# calculate safe distance, where SELss is 145 dB, corresponds to Eq. (6) in manuscript
library(lamW)
safe_distance <-(slope*lamW::lambertW0(-(10^((-intercept+sheq)/slope)*A*log(10))/slope))/(A*log(10))
print(safe_distance) # 5604 m
# calculate SELss for safe distance to cross check
Rk <- safe_distance
SELss <- intercept+slope*log10(Rk)-A*Rk
print(SELss) #must be equal to sheq
# Calculate cumulative SEL for all received pile driving strikes on flight track up to the safe distance
# corresponds to Eq. (6) in the manuscript and results presented in Table II
library(pracma)
dist.start <- 2399 #corresponds to minimum deterrence distance, SELcum must be equal to TTS onset
speed <- 6.1 #m/s, highest reported swim speed
max_sel_cum <- 10*log10(10^(1/10*intercept)/(pulse*speed)*(-1)*(A/10*log(10))^(-slope/10-1)*(incgam(x = A/10*log(10)*safe_distance,a = 1+slope/10)-incgam(x = A/10*log(10)*dist.start,a = 1+slope/10)))
print(max_sel_cum) # 175 dB re 1 μPa2 s, TTS onset, minimum deterrence distance
# test for multiple swim speeds, generate results of Table II
speed_all <- c(6.1,4.3,3.3,.9) # all simulated speed levels
for(s in 1:length(speed_all)){
speed <- speed_all[s]
hp.pos <- seq(from = 750, by=speed*pulse, to = safe_distance) #simulated harbor porpoise positions at time of strikes
max_SEL_cum<-c()
for (i in 1:length(hp.pos)){
max_SEL_cum[i]<- 10*log10(as.numeric(sum((10^ ((intercept+slope*log10(hp.pos)-A*hp.pos) /10))[length(hp.pos):i])))
}
det <- (hp.pos[max(which(max_SEL_cum>TTS_onset))]) #minimum deterrence distance to avoid TTS
strikes <-((safe_distance-det)/speed)/pulse #strikes
time <-((safe_distance-det)/speed) #time in s
strikes*pulse
time
print(c(det,strikes,time/60)) #results of Table II
}
```

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