FEBRUARY 21 2025

Behavioral reactions of harbor porpoises to impact pile driving noise are predicted by the auditory frequency weighted sound pressure level

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J. Acoust. Soc. Am. 157, 1368–1377 (2025)
https://doi.org/10.1121/10.0035916

JASA ARTICLE

Behavioral reactions of harbor porpoises to impact pile driving noise are predicted by the auditory frequency weighted sound pressure level

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ABSTRACT:
Offshore impact pile driving is a major source of high level underwater noise that can disturb marine mammal behavior tens of kilometers away. Projects involving pile driving are therefore subject to environmental impact assessments, which include modelling of the spatial extent of the behavioral disturbance. Reliable predictions about behavioral reaction distances require robust estimates of the minimum received levels of noise above which animals are likely to respond. Studies of reactions of harbor porpoises to pile driving noise in the wild and playback in captivity were identified, and reaction thresholds were extracted. Thresholds were weighted with the auditory frequency weighting function for VHF-cetaceans, the functional hearing group to which porpoises belong. The thresholds derived from playback studies to animals in captivity could be frequency weighted directly, whereas thresholds from exposure to noise from actual pile driving activities were weighted via a range-dependent weighting factor. Seven studies of porpoise reactions provided a first estimate of a behavioral reaction threshold as a VHF-weighted received level ($L_{p,125\,ms,VHF}$) in the range 95–115 dB re 1 μPa.

https://doi.org/10.1121/10.0035916

(Received 16 November 2023; revised 28 January 2025; accepted 30 January 2025; published online 21 February 2025)
[Editor: Klaus Lucke] Pages: 1368–1377

I. INTRODUCTION

Impact pile driving, in particular related to construction of offshore wind farms, has become a major source of underwater sound in the oceans [e.g., Merchant *et al.* (2020). With this increase follows a justified concern for effects on the marine environment, especially on marine mammals [e.g., Madsen *et al.* (2006)]. There is thus a need—often an explicit legal requirement—for conducting environmental impact assessments as part of the permitting process. Many countries have specific guidelines for this, specifying criteria and exposure limits to prevent physical injury to animals [for example, German Federal Ministry for the Environment and Nuclear Safety (2013) and National Marine Fisheries Service (2024)]. Most guidelines are less specific, however, when it comes to assessment of effects due to disturbance of behavior.

The effects of behavioral disturbance are fundamentally different from permanent hearing loss because individual reactions to sound by themselves rarely have significant impact on the animal on the time scale of months or years. Notable exceptions, which represent the upper end of a range of effects, are strandings of some beaked whale species in response to military sonars [e.g., Fernández *et al.* (2005)] and entanglement in fishing gear related to escape behavior. Most impacts from behavioral reactions are less severe, however, and unlikely to have any immediate consequences for the animals [see, for example, the response severity scale of Southall *et al.* (2021)]. Nevertheless, behavioral effects are often cumulative, which means that the combined effect of numerous, repeated reactions to sounds over time may eventually sum up to an impact large enough to affect the survival and reproductive success of the individual—sometimes described as “death by a thousand cuts” (Todd, 2016). The effect of reacting to a single disturbing sound may be a change in behavior of the animal from one state to another. This means that the significant effect of such a behavioral reaction is on the time budget of the individual: More time is spent on reactions to the noise (no matter what kind of behavior it is—even if the reaction is to freeze and remain silent), and there is less time to spend on other behaviors, such as feeding, resting, and nursing offspring. When viewed this way, even a positive reaction to noise (orientation towards or approach to the source) may be viewed as a potential disturbance because the effect is the same: less time devoted to the behavior that was interrupted by the noise. See Christiansen *et al.* (2010) for an example involving dolphin reactions to tourist boats. If reactions become sufficiently severe and frequent enough, the cumulative impact will affect the survival and reproductive success of the individual. If many animals are affected in this way, this will immediately affect the population, as survival and fecundity directly affect the population growth rate. See Bejder *et al.* (2006) for a dolphin example.

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The terms "behavioral reaction" and "behavioral disturbance" are sometimes used interchangeably, which can lead to confusion as the terms are often used with different specific meanings. This is in particular in regulatory contexts where a "disturbance" may express an unwanted or even illegal impact characterized by a behavioral reaction above some level set by regulation, such as in the U.S. Marine Mammal Protection Act (U.S. Congress, 1973) and the European Habitats Directive (European Commission, 1992). It is beyond the scope of this study to attempt to determine or define what constitutes a behavioral disturbance in a legal sense. For a discussion of differences in meaning of the words, see, for example, the reasoning behind the response severity scale (Southall *et al.*, 2021).

A. Thresholds for onset of behavioral reactions

Central in assessment of impact from pile driving noise are reliable thresholds for onset of behavioral reactions, defined here as received sound levels that are likely to lead to specific reactions (such as fleeing) by the animals exposed to the noise. Such thresholds, expressed as received sound pressure levels or similar metrics, are preferred over simpler measures of reaction distances—the latter typically measured empirically in field studies [e.g., Olesiuk *et al.* (2002) and Mikkelsen *et al.* (2017)]. While reaction distances are useful in evaluation of impact from the particular noise source studied in one site, they are difficult to extrapolate to sources with different source characteristics or environments with different sound propagation characteristics. Such generalized thresholds have turned out to be surprisingly difficult to establish. Much regulation in the U.S. is still based on general thresholds expressed as fixed sound pressure levels. These thresholds were based on very little empirical justification, as this was not available in the 1990s, and instead were set on the basis of expert opinions [see Madsen (2005) for a discussion of problems with the metric itself and Scholik-Schlomer (2015) for a historical account]. Furthermore, the relationship between the received level and response is better characterized by a gradual dose-response curve, indicating an increasing likelihood of a response as well as increasing severity of the response with increasing received level of the noise [e.g., Harris *et al.* (2018) and Tyack and Thomas (2019)].

A comprehensive review of the literature on behavioral responses to sound across all marine mammal species was done by Southall *et al.* (2007) and then revisited (Southall *et al.*, 2021). Southall *et al.* (2007) established the behavioral response severity scale as a common methodology intended to be used for meta-studies comparing results from individual publications. However, despite efforts to apply the methodology to selected groups of cetaceans [e.g., Gomez *et al.* (2016)], little progress has been made towards usable generic dose-response curves. Several authors have criticized the severity scale from Southall *et al.* (2007), questioning, for example, whether the severity score scales well with actual impact on the fitness of animals (Ellison *et al.*, 2012; Tougaard *et al.*, 2015; Wright, 2015), but the most important factor preventing progress may be that too many different species and sound sources are combined in meta-studies without taking species-specific differences and differences between sound sources sufficiently into account. As an alternative to a generalized approach, it is proposed to start with individual species, and—if the approach is successful—expand from the individual examples towards generic models. One of the best-suited candidate species for such an approach is the harbor porpoise (*Phocoena phocoena*), as there is a very large amount of experimental data available, both from studies on wild and captive animals and from studies with a wide range of different sound sources.

B. Sensation level as a useful metric

Whether an animal reacts behaviorally to a sound or not depends on a wide range of factors, including context, nutritional status, and previous experience with the particular sound, as well as differences between individuals. However, the most fundamental factor has to be the perceived loudness of the sound. Everything else being equal, animals are more likely to respond to a sound that is perceived to be louder than one perceived as less loud. Loudness is difficult to measure experimentally [although, see Wensveen *et al.* (2014) and Mulsow *et al.* (2015)] and is therefore often approximated by the sensation level, which is the sound level above the hearing threshold for a particular sound (Nedwell *et al.*, 2007; Ellison *et al.*, 2012; MacGillivray *et al.*, 2014; Miller *et al.*, 2014; Tougaard *et al.*, 2015). Sensation level depends first and foremost on two parameters: frequency and duration. Sounds in the frequency range where an animal has good hearing are perceived as louder than sounds of the same sound pressure level, but at the edges of the hearing range. Likewise, longer sounds are perceived as louder than shorter sounds, up to durations equal to the auditory temporal integration time (on the order of some hundred milliseconds) [Johnson (1968), Kastelein *et al.* (2010a), Kastelein *et al.* (2010b); for review, see Erbe *et al.* (2016)]. The way to account for frequency is to perform an auditory frequency weighting with a filter resembling an inverted audiogram[1] [for porpoise examples, see Nedwell *et al.* (2007), Terhune (2013), Hermannsen *et al.* (2015), and Tougaard and Beedholm (2019)], and the way to account for duration is to perform a running root-mean-square average (rms-average) with a time constant approximating the auditory integration time [125 ms, as used by Tougaard *et al.* (2015) and Tougaard and Beedholm (2019)].

Here, relevant empirical measurements of thresholds for negative phonotaxy of porpoises for pile driving noise are reviewed, specifically to test the hypothesis that response thresholds are predicted by sensation level (as a proxy for perceived loudness). Based on this, a threshold range for onset of negative phonotaxy of porpoises to pile driving noise is identified, paving the road for establishing actual dose-response relationships.

II. METHODS

Relevant studies on responses of harbor porpoises to pile driving noise were identified in the literature. The nature of the responses differed among studies. In field studies, the response studied is typically negative phonotaxis—moving away from the sound—quantified either by visually tracking animals or by acoustically detecting changes in vocalizations recorded by passive acoustic monitoring. Such behaviors correspond to levels 5–6 on the response severity scale of Southall *et al.* (2021). (The scale tops at level 9.) Animals in captivity are on one hand easier to study, and more subtle changes in behavior can be detected, and on the other hand more restricted in the types of behavior they can display. In the captive studies included here, the responses of porpoises were quantified as changes in respiration rate and increase in distance to the sound source, used as proxies for negative phonotaxy. On the response severity scale for captive studies by Southall *et al.* (2021) this corresponds to levels 1–2 on a scale that tops at level 4.

Studies were included if a response threshold was given by the authors, expressed as either a single-strike sound exposure level ($L_{E,SS}$) or sound pressure level (L_p), or if such a threshold could be readily implied. Furthermore, thresholds had to be expressed directly as auditory frequency weighted levels, or sufficient spectral information had to be provided to allow a frequency weighting of the threshold.

A. Auditory weighting functions

Several auditory frequency weighting functions have been proposed for porpoises (Nedwell *et al.*, 2007; Southall *et al.*, 2007; Terhune, 2013; Tougaard *et al.*, 2015; Southall *et al.*, 2019). As they are all, in various ways, derived from the porpoise audiogram [Kastelein *et al.* (2002); revised by Kastelein *et al.* (2010a)], they are conceptually very similar. Among the proposed weighting functions is the very high frequency (VHF) cetacean weighting function, derived from measurements of thresholds for onset of temporary threshold shifts (TTSs) and a group audiogram for porpoises (Southall *et al.*, 2019). VHF-weighting is established as a *de facto* standard for use in impact assessments related to hearing loss and auditory injury for porpoises and other VHF-cetaceans. See Tougaard *et al.* (2022) for review of newer data not included in the analysis by Southall *et al.* (2019). For behavioral reactions to noise, the review by Tougaard *et al.* (2015) suggested that the inverted porpoise audiogram would be appropriate as a weighting function for predicting onset of negative phonotaxy to noise pulses such as impact pile driving,[2] pingers, and seal scarers. As the shape of the VHF-weighting function is very similar to the shape of the porpoise audiogram, except for the highest frequencies that are of little relevance for pile driving noise (Fig. 1), the VHF-weighting function of Southall *et al.* (2019) can be used directly even on behavioral data. Thus, to retain simplicity and because the tools are already available (Tougaard and Beedholm, 2019), the VHF auditory weighting function was selected for this meta-analysis. However, this choice should be considered interim and subject to periodic revisits, in the same way as is the case for the application to assessment of auditory injury (Tougaard *et al.*, 2022).

If a recorded waveform is available of a noise pulse, VHF-weighting can readily be performed by the tools of Tougaard and Beedholm (2019) or similar ones: This is rarely the case for studies identified in the literature, however. Two different methods were therefore used to derive VHF-weighted thresholds from the studies analyzed, described below as one used on playback studies in captivity and a second used on results from studies on wild porpoises exposed to real pile driving.

1. Frequency weighting in playback studies (range independent)

If a power spectrum of the playback signal was available, as in the example from Kastelein *et al.* (2013) in Fig. 2(A), the frequency weighting could be performed directly on the decidecade levels[3] by adding the (negative) weighting factor for each decidecade center frequency, calculated from Eq. (2) in Southall *et al.* (2019), whereby the weighted decidecade spectrum [broken curve in Fig. 2(A)] was obtained. The total unweighted level of the playback signal was found by adding the energy of all decidecade bands,

$$L_E = 10\log_{10}\left(\sum_i^n 10^{\left(L_{E,ddec}(f_i)/10\right)}\right)\mathrm{dB}, \tag{1}$$

where $L_{E,ddec}(f_i)$ is the sound exposure level in the ith decidecade band with center frequency f_i. The total weighted sound exposure level $L_{E,VHF}$ was found as the sum of decidecade sound exposure levels, each band weighted by adding

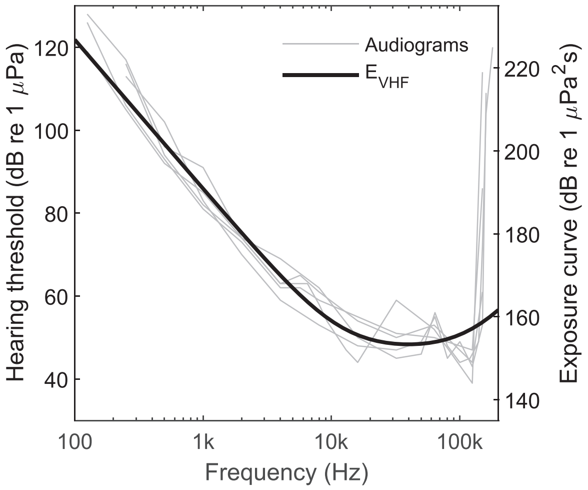

FIG. 1. Comparison of the available audiograms from harbor porpoises (Kastelein *et al.*, 2002; Kastelein *et al.*, 2010a; Kastelein *et al.*, 2015; Kastelein *et al.*, 2017) and the inverted VHF-weighting function of Southall *et al.* (2019) (called the exposure function). The y axes are different as the metric used to characterize hearing thresholds (sound pressure level) is different from the metric used to characterize onset of temporary thresholds shifts (sound exposure level). The slopes of the two curves are very similar, however.

the appropriate value of the VHF-weighting function, $W_{VHF}(f_i)$, for the ith band

$$L_{E,VHF}=10\log_{10}\left(\sum_{i}^{n}10^{\left(\left[L_{E,ddec}(f_i)+W_{VHF}(f_i)\right]/10\right)}\right)\mathrm{dB}. \tag{2}$$

For a particular spectrum, the weighting factor $W_{VHF,playback}$ was then found as the difference between the unweighted and the weighted levels:

$$W_{VHF,playback} = L_E - L_{E,VHF}\ \mathrm{dB}. \tag{3}$$

This weighting factor is specific to each experiment, as it changes with the spectrum of the sound, and separate weighting factors were used for the different studies analyzed, as described for each experiment below.

2. Range-dependent frequency weighting

Frequency weighting of noise from real pile driving is complicated by the frequency-dependent absorption of sound with distance to the piling site. The difference between the unweighted and the weighted spectrum changes with distance as higher frequencies suffer larger absorption than lower frequencies do. This is illustrated by spectra representing averages of a very large number of measurements of impact pile driving noise in the German Bight, replotted from Bellmann *et al.* (2020) in Fig. 2(B). Frequency weighting of these spectra was done in the same way as described above for the captive studies, except that each of the four spectra (for distances 0.75, 1.5, 10, and 20 km) was treated separately, resulting in four different weighting factors [black circles in Fig. 2(C)]. A log-linear straight line was fitted to the data points, which provided an expression used to estimate the range-dependent weighting factor $W_{VHF}(r)$ for distance r km from the piling site:

$$W_{VHF}(r) = 8.85 \times \log_{10}(r)\mathrm{dB} + 36.5\ \mathrm{dB}. \tag{4}$$

This analysis is strictly only valid for the measurements analyzed by Bellmann *et al.* (2020), but as these were all measured from impact pile driving of monopiles in the German Bight, without noise abatement (air bubble curtains or similar), Eq. (4) was considered applicable to similar types of pile driving in comparable environments. This meant that received sound exposure levels (L_E) at onset of porpoise reactions to impact pile driving noise, indicated to occur at some range r, could be VHF-weighted by application of the weighting factor to the unweighted threshold level

$$L_{E,VHF}(r) = L_E(r) - W_{piling,VHF}(r)\ \mathrm{dB}. \tag{5}$$

B. Relationship between sound exposure level and sound pressure level

Most studies where received levels of impact pile driving noise has been measured report values as single-strike sound exposure level ($L_{E,SS}$) as this is a relevant metric for assessing risk of inflicting temporary and permanent hearing loss (Finneran, 2015; Southall *et al.*, 2019). However, when assessing the likelihood of eliciting a behavioral reaction, the short-term rms-average ($L_{p,125\ ms}$) is more appropriate

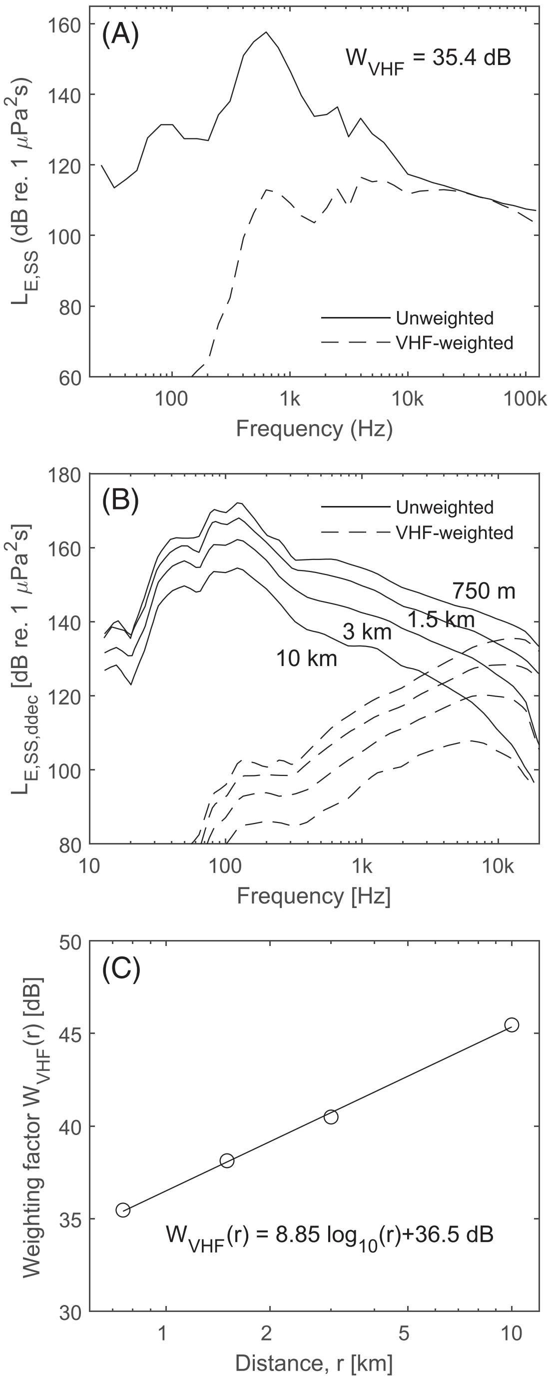

FIG. 2. (A) Decidecade power spectrum of the impact pile driving playback noise used by Kastelein *et al.* (2013) shown both unweighted and VHF-weighted. The weighting factor W_{VHF} used to convert from unweighted to VHF-weighted sound exposure levels was found as the difference between the two curves. See text for additional explanation. (B) Average frequency spectra of unabated pile driving noise at four different distances from the piling site. Replotted from Bellmann *et al.* (2020). Broken lines indicate VHF-weighted spectra to illustrate the effect of weighting. (C) VHF-weighting factor, being the difference (in energy) between the unweighted and the weighted power spectra, with increasing distance from the piling site. Included is the equation for the best fitting log-linear curve to the data.

(Tougaard *et al.*, 2015), as this metric correlates better with the perceived loudness of the sound than does $L_{E,SS}$. For short sounds, shorter than the rms-averaging time (125 ms), there is a fixed relationship between $L_{E,SS}$ (re 1 μPa^{2}s) and $L_{p,125\ ms}$ (re 1 μPa)

$$\begin{aligned} L_{p,125\,ms} &= L_{E,SS}(r) - 10\log_{10}(0.125)\ \mathrm{dB} \\ &= L_{E,SS} + 9\ \mathrm{dB}. \end{aligned} \tag{6}$$

Pile driving sounds recorded close to the piling site are very short, considerably less than 125 ms, but as they propagate to larger distances, there is a stretching of the signal due to multi-path propagation and frequency-dependent differences in sound speed [e.g., Hastie *et al.* (2019) and Bellmann *et al.* (2020)]. The effect is not large at the ranges involved in the studies analyzed (up to 25 km) and unlikely to add more than a few dB of uncertainty. The conversion factor of Eq. (6) (9 dB) is thus also supported by empirical data from pile driving in the German Bight (Bellmann *et al.*, 2020).

III. RESULTS

Five studies were identified where weighted reaction thresholds of harbor porpoises to impact pile driving noise could be derived. Three of these are studies on full-scale pile driving in the field (Dähne *et al.*, 2013; Brandt *et al.*, 2018; Graham *et al.*, 2019), where responses of porpoises were studied by passive acoustic monitoring, and two are studies of playback of pile driving noise at reduced levels to porpoises in captivity (Kastelein *et al.*, 2013; Kastelein *et al.*, 2022). In addition to these studies, two reviews were included: Tougaard *et al.* (2015), where reaction thresholds of wild porpoises to a range of different sounds (including pile driving) were derived; and Wensveen (2015), who conducted a similar review on studies on captive porpoises. These two studies contain sounds other than impact pile driving but were included in the present analysis because they provided the first indication that audiogram weighting could be appropriate for behavioral data. All studies are presented individually below, and received levels at onset of behavioral reactions derived from each of the studies are compiled in Table I.

Dähne *et al.* (2013) studied reactions of wild porpoises to impact pile driving at the Alpha Ventus offshore wind farm and were able to link reactions to estimated received levels of noise. Reactions were quantified by passive acoustic monitoring of porpoise echolocation and showed a statistically significant response to pile driving (decrease in acoustic detections) 10 km from the piling site, but not at 25 km (no intermediate distances were monitored). The estimated received $L_{E,SS}$ (unweighted) of single pile driving sounds was 139–145 dB re 1 μPa^{2}s at 25 km and 146–152 dB re 1 μPa^{2}s at 10 km. This translates into weighted sound pressure levels, $L_{p,125\ ms,VHF}$, of 99–105 dB re 1 μPa (25 km) and 110–116 dB re 1 μPa (10 km), by application of Eqs. (5) and (6). These figures indicate that wild porpoises react to pile driving noise above VHF-weighted received levels somewhere in the range 99–116 dB re 1 μPa.

Tougaard *et al.* (2015) reviewed the studies available at the time where reactions of wild porpoises to different types of sound had been studied and where the received sound pressure level ($L_{p,125\ ms}$) at the maximum reaction distance was measured or could be estimated [Fig. 3(A)]. Figure 3(B) shows the data replotted with sound pressure levels adjusted by the VHF-weighting factor at the corresponding frequencies [$W_{VHF}(f)$]. The range of thresholds for behavioral responses ($L_{p,125\ ms,VHF}$) was 79–117 dB re 1 μPa, with the largest deviations at higher frequencies. The mean of all studies was 95 dB re 1 μPa.

Wensveen (2015) performed a review similar to Tougaard *et al.* (2015), but on response thresholds obtained from studies on porpoises in captivity, using a wide range of signals, mostly of narrow bandwidth. The range of VHF-weighted thresholds of these studies was 90–136 dB re 1 μPa, with the largest deviations at higher frequencies (all higher than predicted). The mean of all studies was 106 dB re 1 μPa.

Brandt *et al.* (2018) performed a unified statistical analysis of passive acoustic monitoring data on porpoises from construction of seven different offshore wind farms in the German Bight. The porpoise monitoring was complemented by acoustic recordings of the impact pile driving noise, which made it possible to derive a generalized threshold for porpoise reactions to the impact pile driving noise, expressed as the lowest noise level when porpoise detections during piling reached the overall average of all data. This threshold was at a received single-strike sound exposure level ($L_{E,SS}$) of 143 dB re 1 μPa^{2}s (unweighted), reached in a distance between 20 and 30 km from the pile driving site. By application of Eqs. (4) and (5) with a weighting factor calculated for 25 km (49 dB), this converts into a received level $L_{p,125\ ms,VHF}$ of 103 dB re 1 μPa. No indication of uncertainty is given on the threshold. For the purpose of plotting the threshold in Fig. 4 an arbitrary range of ±5 dB was selected.

Graham *et al.* (2019) studied reactions to pile driving at the Beatrice offshore wind farm in Moray Firth, Scotland, by passive acoustic monitoring and modelling of received sound exposure levels at different distances. Based on this, they derived a dose-response curve linking received sound pressure level with probability of detecting a decrease in porpoise acoustic activity. The unweighted sound exposure level, $L_{E,SS}$, corresponding to a 50% probability of reaction, was approximately 145 dB re 1 μPa^{2}s for the first pile driving event, consistent with the results of Dähne *et al.* (2013) and Brandt *et al.* (2018). As construction went on, the response threshold increased, indicating a diminishing response with time (habituation). Graham *et al.* (2019) also performed an auditory frequency weighting of received levels with an inverted porpoise audiogram as weighting function. This procedure is comparable to weighting with the VHF-function of Southall *et al.* (2019), but not identical. In addition to smaller differences in the exact shape of the

TABLE I. List of studies on harbor porpoises where a frequency weighted threshold associated with impact pile driving could be derived. For each study is indicated what type of reaction was used to determine the threshold region for reactions and the range of thresholds estimated (VHF-weighted as described in the text).

Study	Reaction	Threshold (VHF-weighted)	Comment
Dähne *et al.*, 2013	Decrease in acoustic detections	100–116 dB re 1 μPa	Pile driving, passive acoustic monitoring at Alpha Ventus offshore wind farm; lower and upper estimates of threshold given
Kastelein *et al.*, 2013	Change in breathing rate and distance to source	95–101 dB re 1 μPa	Playback of pile driving noise in captivity; animal ID M02
Tougaard *et al.*, 2015	Decrease in visual or acoustic detections	79–117 dB re 1 μPa (range) 95 dB re 1 μPa (mean)	Multiple sound types in the wild, including pile driving
Wensveen, 2015	Change in breathing rate and distance to source	91–135 dB re 1 μPa (range) 106 dB re 1 μPa (mean)	Multiple sound types in captivity
Brandt *et al.*, 2018	Decrease in acoustic detections	103 dB re 1 μPa (mean)	Pile driving, metastudy; passive acoustic monitoring of six wind farms in the German Bight
Graham *et al.*, 2019	Decrease in acoustic detections	110 dB re 1 μPa (50% response probability) 90–129 dB re 1 μPa (5%–95% response probability)	Pile driving, passive acoustic monitoring at Beatrice offshore wind farm; response to first pile driving.
Kastelein *et al.*, 2022	Change in breathing rate and distance to source	<100 dB re 1 μPa	Playback of pile driving noise in captivity; animal ID F05

weighting function, the main difference is that the weighting function of Graham *et al.* (2019) is normalized to 0 dB at the frequency of best hearing, whereas the VHF-function of Southall *et al.* (2019) is offset to match the audiogram by the parameter T_0 (46 dB re 1 μPa). Therefore, 46 dB was added to the sound exposure levels of Graham *et al.* (2019) to make them comparable to VHF-weighted levels and further converted to $L_{p,125\ ms,VHF}$ by adding another 9 dB [Eq. (6)]. This resulted in a dose-response relationship spanning from 5% response probability at 80 dB re 1 μPa to 95% response probability at 119 dB re 1 μPa (Fig. 4).

Kastelein *et al.* (2013) played impact pile driving sounds at reduced levels to a porpoise in captivity and showed that the respiration rate increased significantly at received sound pressure levels (L_p) above 136 dB re 1 μPa, but not at 130 dB re 1 μPa. As the decidecade spectrum of the pile driving sound used for playback was given [Fig. 2(A)], a VHF-weighting could be performed by calculating the difference between the unweighted and the weighted spectra (Eq. (3), amounting to a weighting factor of 35 dB: This means that the $L_{p,125\,ms,VHF}$ at threshold for behavioral response in that study was between 95 and 101 dB re 1 μPa.

In a similar setup, but with a different animal, Kastelein *et al.* (2022) tested whether responses of a captive porpoise to playback of impact pile driving noise were best predicted by weighted or unweighted $L_{E,SS}$. Response to the playback was quantified by two metrics: respiration rate and distance between porpoise and sound source. Both metrics showed increased response with increasing $L_{E,SS,VHF}$. Respiration rate increased significantly compared to baseline for sounds at $L_{E,SS,VHF}$ above 99 dB re μPa^{2}s, whereas the mean distance between porpoise and sound source increased for all sounds down to the lowest $L_{E,SS,VHF}$ of 91 dB re μPa^{2}s. By application of Eq. (6) these levels translate into a threshold expressed as $L_{p,125\ ms,VHF}$ of 100 dB re 1 μPa or lower, consistent with the result of Kastelein *et al.* (2013).

IV. DISCUSSION

Response thresholds of porpoises to a wide range of underwater sounds, including impact pile driving noise, were well predicted by the received sound pressure levels calculated over an interval corresponding to the integration time of the porpoise ear (125 ms) and auditory frequency weighted with the VHF-weighting function. This provides strong support to the hypothesis that perceived loudness of the sounds is the main factor determining whether porpoises respond to the sound or not. Further support comes from the individual studies of reactions to impact pile driving noise, both in captivity and in the wild (Table I and Fig. 4). It is difficult to compare the studies directly, as they differ considerably in methodology and details available for a proper numerical meta-analysis that could result in a common dose-response curve. However, when looking at the results in Fig. 4, it is seen that only limited responses are reported at received levels below 90 dB re 1 μPa (VHF-weighted) and that all studies report strong responses above 110 dB re 1 μPa. It is noteworthy in this context that the studies span exposures to sources located anywhere from a few meters away (captive animals) to tens of kilometers (wild animals), yet they show increased probability of response in the same range of received levels, without any systematic differences between close and distant sources. Also, noteworthy is that results were obtained with very different methods (visual observations and passive acoustic monitoring). Combined, the results support the hypothesis that the VHF-weighted received level of a sound is a robust first approximation for predicting whether porpoises will respond to the sound or not.

The importance of received level, rather than distance to source, in predicting responses to a sound has also been demonstrated in northern bottlenose whale (*Hyperoodon ampullatus*)—where distance to source, at least up to 28 km, did not explain reactions (Wensveen *et al.*, 2019)—and in

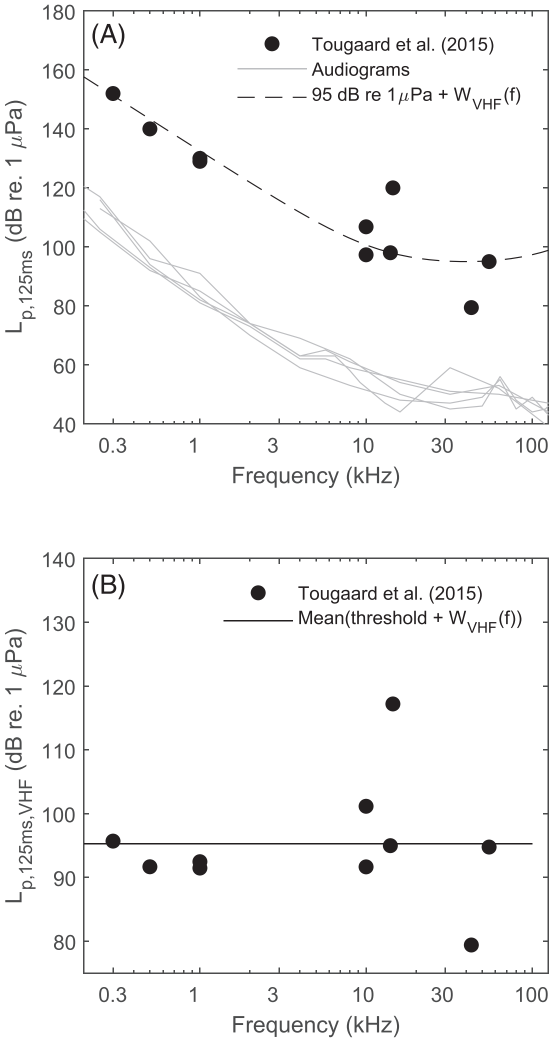

FIG. 3. (A) Results of Tougaard *et al.* (2015) replotted. (B) Estimated sound pressure level rms-averaged over 125 ms ($L_{p,125\ ms}$) and weighted by the VHF-weighting function of Southall *et al.* (2019) at threshold for behavioral responses (fleeing) when exposed to various types of underwater noise pulses (impact pile driving, seal scarers, and gillnet pingers). (B) Same data as VHF-weighted sound pressure levels, together with the mean.

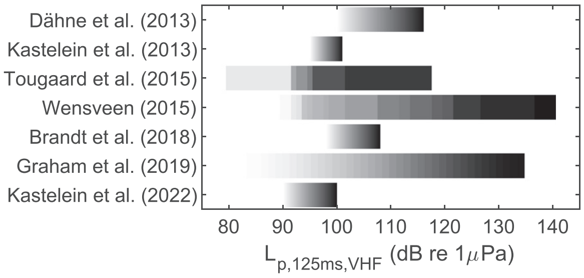

FIG. 4. Range of received sound pressure levels (VHF-weighted rms-average over 125 ms) that resulted in behavioral responses in harbor porpoises, compiled from seven studies. Responses varied from decrease in acoustic detection for wild animals to decrease in breathing rate and increase in distance to source in captive animals, all reactions regarded as proxies for negative phonotaxy. The greyscale indicates probability of response, ranging from 0% to 100%. See Table I and text for details about individual studies.

humpback whales (*Megaptera novaeanglicae*), in a carefully conducted controlled exposure study (Sprogis *et al.*, 2020). At larger distances of several tens of kilometers, however, there are indications that distance to source (Harris *et al.*, 2016) and behavioral state (Southall *et al.*, 2016) also play a role in determining whether animals respond or not. For beaked whales in particular, there are indications that responses to very distant sources (more than 50 km) are lower than to sources closer to the animal, despite identical received levels (DeRuiter *et al.*, 2013; Southall *et al.*, 2016). The results summarized in Table I suggest that for porpoises, there is no decrease in response to the sound that cannot be predicted from the received level, at least up to distances of 20–30 km.

When expressed as VHF-weighted sound pressure levels, the response thresholds of porpoises to impact pile driving noise and other sounds were in the range 90–110 dB re 1 μPa, which corresponds to a sensation level above hearing threshold between 45 and 65 dB. This sensation level is found by subtracting the threshold at frequencies of best hearing [roughly 15–150 kHz (see Fig. 1)]—about 45 dB re 1 μPa—from the weighted thresholds. Sensation level at threshold for behavioral reactions to noise has not been quantified directly for other odontocete species, but can be inferred from experimental results, primarily in controlled exposure studies with sonar-like signals. Substantial variation in reaction thresholds is seen in these experiments, some higher than the porpoise threshold, some lower. For example, Tyack *et al.* (2011) saw reactions in beaked whales (*Mesoplodon densirostris*) to 3.5–4 kHz signals at received sound pressure levels of 138–142 dB re 1 μPa, which is about 60 dB above the hearing threshold at 5 kHz (Pacini *et al.*, 2011). DeRuiter *et al.* (2013) measured reaction in another beaked whale, *Ziphius cavirostris*, also to 3.5–4 kHz signals, at received levels between 98 and 127 dB re 1 μPa, corresponding to sensation levels between 20 and 50 dB (assuming same hearing threshold as *M. densirostris*), and Miller *et al.* (2014) documented reactions in killer whales (*Orcinus orca*) to 1–2 kHz and 6–7 kHz signals at received levels between 94 and 166 dB re 1 μPa, corresponding to sensation levels between 5 and 75 dB [comparison to audiogram from Branstetter *et al.* (2017)]. The variation in these estimates indicates that more studies are needed on these species in order to test whether perceived loudness is also a useful predictor of response in other odontocete species.

A. Use in impact assessments

The review of available data on behavioral reactions to noise performed above suggests that a generic dose-response relation for responses to impact pile driving noise is provided by the VHF-weighted, root-mean-squared sound pressure levels ($L_{p,125\ ms,VHF}$) and suggests that this could be valid for other types of sounds as well. The range of VHF-weighted received sound pressure levels at which animals responded consistently across studies was found to be between 90 and 110 dB re 1 μPa. If a proper dose-response curve can be derived, either from the existing data or through dedicated experiments, this relationship can be used to predict the extent of the zone of disturbance around a given sound source. If the average density of porpoises is also known in the impacted area, it is possible to estimate the number of animals impacted by the sound source. Such modelling can also include the effect of noise abatement technologies, such as air bubble curtains, thereby allowing assessment of predicted efficacy of mitigation measures prior to permitting the noisy activity (pile driving or other).

As an interim solution, until a credible dose-response relationship is derived, one can approximate the relationship with a single number—a response threshold. Thresholds are inherently statistical phenomena, and there are several problems associated with selecting a single number to be used in modelling rather than an entire dose-response curve, most importantly underestimation of possible impact on the most sensitive part of a population of animals (Tyack and Thomas, 2019). A useful feature, however, of a single number used as a threshold is that the impacted area scales well with changes in source properties, sound propagation conditions, and application of noise abatement. By modelling several different scenarios (with and without noise abatement or for different hydrographical conditions), the relative changes in predicted impact can be evaluated and informed choices made about when and how to install the monopiles with the least disturbance as a result, even if the absolute size of the impacted area or number of animals exposed is somewhat underestimated. Such an approach was, for example, taken in the recent update of the Danish guidelines for impact assessment of pile driving (Danish Energy Agency, 2023; Lützen *et al.*, 2023). Here, a pragmatic choice of 103 dB re 1 μPa ($L_{p,125\ ms,VHF}$) was used, being the result of a meta-study involving measurements from seven different offshore wind farms (Brandt *et al.*, 2018).

SUPPLEMENTARY MATERIAL

See the supplementary material for the data plotted in Figs. 1 and 2, as well as data extracted from Wensveen (2015).

ACKNOWLEDGMENTS

This study was funded by the Danish Energy Agency and the Danish Environmental Protection Agency (Vildtkontrakten). An earlier presentation of some of the results is available as a report to the Danish Energy Agency (Tougaard, 2021). The final text benefitted significantly from insightful and constructive comments from several anonymous reviewers.

AUTHOR DECLARATIONS

Conflict of Interest

The author has no conflicts to disclose.

DATA AVAILABILITY

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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[1] In practice, equal loudness contours are only approximated by iso-sensation level contours, with larger mismatch at higher loudness levels. Onset of behavioral reactions, however, is often at low loudness levels, where the mismatch is small and sensation level therefore a good proxy for loudness.

[2] The word "impact" when used in connection with pile driving is only a reference to the method of installation by means of percussive blows to the foundation by a hydraulic hammer, not an indication of impact on animals. Alternative non-impact methods are available, such as vibropiling, that generate significantly lower levels of underwater noise.

[3] Following ISO 18405:2017 (2017), the term "decidecade band" is used to refer to a bandwidth of 1/10 decade, traditionally referred to as a 1/3 octave band. See Ainslie *et al.* (2022) for further information.

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