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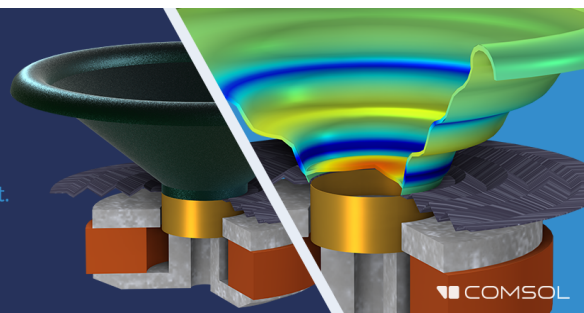
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Thresholds for noise induced hearing loss in harbor porpoises and phocid seals

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ABSTRACT:

Intense sound sources, such as pile driving, airguns, and military sonars, have the potential to inflict hearing loss in marine mammals and are, therefore, regulated in many countries. The most recent criteria for noise induced hearing loss are based on empirical data collected until 2015 and recommend frequency-weighted and species group-specific thresholds to predict the onset of temporary threshold shift (TTS). Here, evidence made available after 2015 in light of the current criteria for two functional hearing groups is reviewed. For impulsive sounds (from pile driving and air guns), there is strong support for the current threshold for very high frequency cetaceans, including harbor porpoises (*Phocoena phocoena*). Less strong support also exists for the threshold for phocid seals in water, including harbor seals (*Phoca vitulina*). For non-impulsive sounds, there is good correspondence between exposure functions and empirical thresholds below 10 kHz for porpoises (applicable to assessment and regulation of military sonars) and between 3 and 16 kHz for seals. Above 10 kHz for porpoises and outside of the range 3–16 kHz for seals, there are substantial differences (up to 35 dB) between the predicted thresholds for TTS and empirical results. These discrepancies call for further studies.

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I. INTRODUCTION

Underwater noise from human activities at sea is known to affect marine organisms that are sensitive to sound. One such activity that has received substantial attention is percussive pile driving of monopile foundations for offshore wind turbines. This concern has prompted many countries to install regulatory procedures for proper impact assessment and permitting of activities (for example, [German Federal Ministry for the Environment and Nuclear Safety, 2013](#); [Danish Energy Agency, 2016](#)) and stimulate development of efficient mitigation measures, such as air bubble curtains (see, e.g., [Dähne et al., 2017](#)). Noise impact criteria and associated exposure limits are central to regulation and, therefore, such criteria have been the topic of significant research efforts. A key focus of discussion, initiated by the first general proposal for criteria and thresholds by [Southall et al. \(2007\)](#), has been the issue of auditory frequency weighting of sound for assessment and regulatory purposes. Frequency weighting is a filtering of the noise under concern with a filter shape that reflects the different impacts of different frequencies on the auditory system of a given species. Through frequency weighting, regulation and decision-making based on broadband (unweighted) sound levels can be avoided as reliance on broadband levels can lead to significant errors in impact assessments ([Tougaard et al., 2015](#); [Tougaard and Dähne, 2017](#)).

The most recent guidance for marine mammals on the issue of thresholds for onset of temporary hearing loss and injury to the auditory system is the comprehensive presentation by [Southall et al. \(2019\)](#), which was based on the authoritative review of experimental data and derivation of weighting functions by [Finneran \(2015\)](#), followed by adoption as interim criteria by the U.S. [National Marine Fisheries Service \(2016, 2018\)](#). These criteria are based on measurements of noise levels required to induce 6 dB of temporary threshold shift (TTS) in captive animals, which are all derived from experimental data published before the review by [Finneran \(2015\)](#). From these thresholds, the higher levels required to induce minimal permanent threshold shift (PTS) in marine mammals are extrapolated. These TTS and PTS thresholds then constitute the recommended exposure limits for application in environmental assessments. However, new findings must continuously be added to the body of empirical evidence; [Southall et al. \(2007\)](#) and [Southall et al. \(2019\)](#) anticipated and encouraged an iterative process, involving regular reassessments, followed by adjustments of criteria and thresholds when appropriate. Since 2015, a considerable number of novel results from harbor porpoise (*Phocoena phocoena*) and phocid seals have become available. Harbor porpoise, a very high frequency (VHF) cetacean, and harbor seal (*Phoca vitulina*), a phocid seal with a broadband hearing range, are of particular interest with respect to pile driving as they are acoustically

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sensitive and among the most common marine mammals in shallow Western European waters—a center of the rapidly expanding offshore wind farm industry. These new results, therefore, call for revisiting the synthesis culminating in Southall *et al.* (2019). Here, we do that specifically by testing the predictions of the weighting curves against new experimental data for these two species to address whether a revision of weighting curves and exposure thresholds is needed to inform the most appropriate mitigation measures.

II. SOME DEFINITIONS

Although terminology required for the discussion of thresholds and frequency weighting are provided by Southall *et al.* (2019), some key definitions regarding impulsive sounds and frequency weighting are revisited below for convenience.

A. Impulsive sounds

Some confusion exists in the literature regarding the use of the terms “pulse” and “impulse” as characterization of “brief” sound signals. The confusion is partly based in semantics and partly by the lack of clear definitions. What is important, however, is that this group of acoustic signals has been identified as differing from other sounds in that they are generally believed to be more likely than other sounds to inflict damage to biological tissue, including hearing organs. These impulsive sounds have some shared characteristics that make them stand out from other sounds: short rise time from start to peak pressure, often followed by a slower decay; short duration, typically not more than a second and often much less; and large bandwidth (Southall *et al.*, 2007; National Marine Fisheries Service, 2016, 2018; Hastie *et al.*, 2019). It is not possible to provide a more exact definition than the above, but it may be helpful to consider some examples. Good examples of sources that produce sounds with the above characteristics are underwater explosions, seismic air guns, and percussive pile driving. This group of sounds is referred to as impulses or impulsive sounds in some texts (National Marine Fisheries Service, 2016, 2018; Southall *et al.*, 2019) and pulses in others (Southall *et al.*, 2007), differing from other sounds, which have been referred to as non-pulses (Southall *et al.*, 2007) and non-impulsive sounds (National Marine Fisheries Service, 2016, 2018). The non-impulsive sounds may have some of the listed properties of impulsive sounds but not all. Examples of sources producing such non-impulsive sounds are sonars (less sharp onset, often narrow bandwidth, or frequency modulated) and seal scarers (long duration, narrow bandwidth, although often with strong harmonics). Further, impulsive sounds gradually lose their impulsive characteristics through propagation over larger distances and will, therefore, no longer be classifiable as impulses beyond some range from the source (Southall *et al.*, 2007; Southall, 2021). The range at which this gradual transition occurs depends heavily on the frequency spectrum of the sound and the environment, but for pile driving sounds, it

has been estimated to occur at a range between a few km to tens of km (Hastie *et al.*, 2019).

Whereas the term “impulsive sound” probably is the most consistent and precise term for the abovementioned sounds with all of the distinctive features, this term is also used in a broader sense in other contexts, such as in the EU Marine Strategy Framework Directive (European Commission, 2008). Here, the term “impulsive” also includes short non-pulses/non-impulses and is used to separate these brief sounds from more continuous sources, such as ships and offshore structures (bridges, platforms, renewable energy installations, etc.). In the following, the more restrictive definition of impulsive sounds *sensu* Southall *et al.* (2019) is used.

B. Auditory frequency weighting functions

Animals do not hear equally well at all frequencies. For humans, where enormous empirical evidence is available in the form of thousands of patients with known noise exposure history and measured hearing loss, the consensus is to weigh noise exposures with a curve roughly resembling the inverted audiogram. This so-called dBA-weighting, provides the best overall prediction of risk of injury (see Houser *et al.*, 2017 for an extensive review). For marine mammals, the first auditory weighting curves were proposed by Southall *et al.* (2007), the so-called *M*-weighting curves, justified by the shape of equal-loudness curves for loud sounds. Although conceptually important, this justification and the *M*-curves themselves are now considered obsolete and have been replaced by weighting functions resembling inverted audiograms (Tougaard *et al.*, 2015; National Marine Fisheries Service, 2016, 2018; Southall *et al.*, 2019). Because experimental data are only available for a limited number of species—but also to simplify regulation and assessment procedures—marine mammals have been divided into a number of “functional hearing groups” within which all members are assumed to have roughly the same hearing capabilities and, therefore, similar sensitivity to noise. Out of the total of six hearing groups defined by Southall *et al.* (2019), two groups of particular relevance to this review are “phocid carnivores” in water (PCW) for the seals and “very high frequency cetaceans”¹ for porpoises.

The PCW and VHF weighting functions are both inverted *U*-shapes and derived from the TTS data by adjusting the parameters of the equation describing the curve to obtain the best possible fit to the data. See National Marine Fisheries Service (2018) for details and Tougaard and Beedholm (2019) for a practical implementation.

III. METHODS

Empirical data on TTS onset thresholds were compiled from the literature. For studies already included in Finneran (2015), onset TTS thresholds, i.e., the sound exposure level (SEL) required to induce 6 dB of TTS measured shortly after cessation of the fatiguing sound, were taken from his review. For all of the newer studies, the TTS onset threshold was derived by the same method used by Finneran (2015),

which was fitting a curve to the TTS growth function, describing the amount of onset TTS as function of the SEL of the fatiguing sound. The TTS growth function is described by

$$\text{TTS}(\text{SEL}) = a \log_{10}(10^{(\text{SEL}-b)/10}), \quad (1)$$

where a and b are constants that are adjusted by a least squares method to obtain the best fit to the data (Finneran, 2015). When hearing was tested at different frequencies, only the TTS at a test frequency about half an octave above the fatiguing sound was used as this was the frequency with the highest induced TTS in most of the studies. Once parameters a and b had been estimated for a given experiment, the SEL predicted to result in 6 dB of threshold shift, defined as the TTS onset threshold, was found by rearranging Eq. (1) such that

$$\text{SEL}_{6\text{dB TTS}} = 10 \log_{10}(10^{6/a} - 1) + b. \quad (2)$$

These TTS onset thresholds were compared with thresholds predicted by the exposure function from Southall *et al.* (2019). The exposure function is the weighting function flipped around the horizontal axis and vertically aligned to provide the best fit to TTS onset thresholds.

TTS onset thresholds for broadband, impulsive sounds cannot be compared to the exposure function directly and must be compared to the weighted TTS onset thresholds provided by Southall *et al.* (2019). This was performed with the same method as was used by Tougaard and Dähne (2017), where the decade² frequency spectrum of the fatiguing sound was adjusted in amplitude so that the total energy (sum of all decade bands) equaled the unweighted TTS onset threshold. The weighted threshold could then be found by weighting the individual decade bands with the value of the weighting function at the center frequency of each decade band and subsequently summing the energy of all of the bands.

IV. EMPIRICAL DATA ON TTS SINCE 2015

A substantial number of studies of TTS in porpoises and seals have been conducted in recent years and, thus, a large body of empirical data has become available after the review by Finneran (2015). The results of these studies are summarized below with details provided in Table IV of the Appendix.

A. Harbor seal

Four studies on harbor seals were included by Finneran (2015), two of which related to thresholds for PTS (Kastak *et al.*, 2008; Kastelein *et al.*, 2013a). Seven new publications have appeared after the review (all are listed in the Appendix). One early study (Kastak *et al.*, 1999) was not included by Finneran (2015), likely due to difficulties in quantifying the exposure and thereby, also, the derivation of a TTS onset threshold. All of the thresholds for non-impulsive (narrowband) sounds for phocid seals included by

Southall *et al.* (2019) and more recent thresholds from the literature are shown in Fig. 1.

TTS onset thresholds at fatiguing frequencies 6.5 kHz (Kastelein *et al.*, 2019c) and 16 kHz (Kastelein *et al.*, 2019b) align well with predictions from the PCW weighting, whereas the thresholds were underestimated by considerable amounts at low frequencies (1 and 2 kHz, Kastelein *et al.*, 2020c) and somewhat overestimated at high frequencies (32 kHz, Kastelein *et al.*, 2020e; and 40 kHz, Kastelein *et al.*, 2020g). Both seals in Kastelein *et al.* (2020c) did not show any TTS in response to fatiguing noise at the maximum level (211 dB SEL, unweighted) at 500 Hz and one seal did not show TTS in response to 2 kHz fatiguing noise.

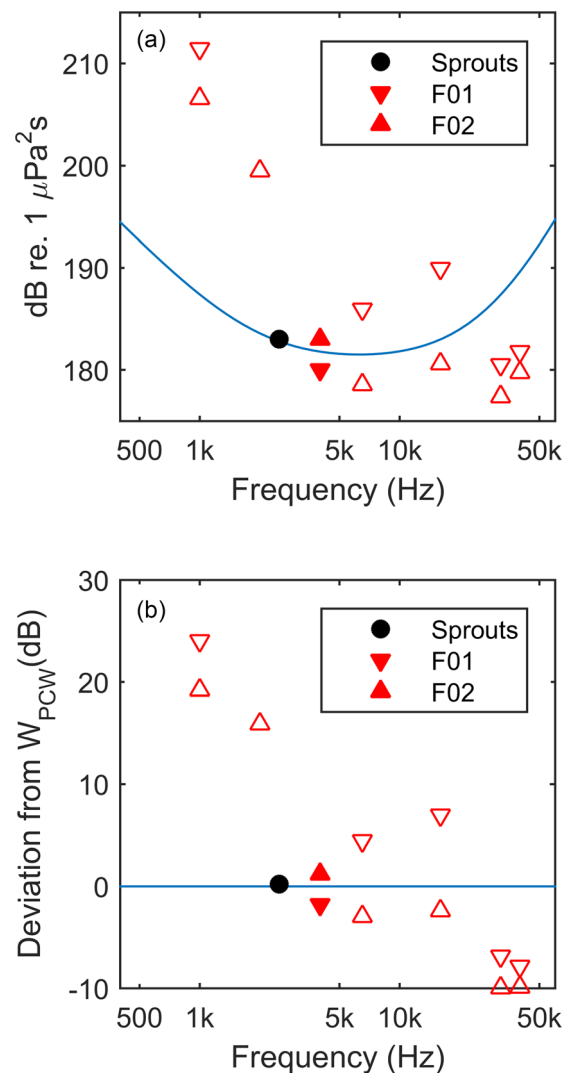


FIG. 1. (Color online) (a) TTS onset thresholds for harbor seals with different symbols indicating individual experimental subjects are shown. The data points until 2015 (included in Southall *et al.*, 2019) are shown with filled symbols, and more recent data are shown with open symbols. The black symbols indicate that the animal was exposed at a stationary position; the red symbols indicate exposure to free-swimming animals. The PCW exposure function, which is the inverted PCW weighting function, is indicated by the blue line (for details, see Southall *et al.*, 2019). (b) The same data as in (a) but normalized to the exposure function (blue line). See Table IV in the Appendix for details on individual experiments.

Three studies have been published for phocid seals since Finneran (2015), involving impulsive (broadband) sounds as fatiguing sounds. One set of experiments on two ringed seals (*Pusa hispida*) and two spotted seals (*Phoca largha*) failed to induce TTS by exposure to air gun pulses at a SEL up to a maximum of 181 dB re $1 \mu\text{Pa}^2 \text{ s}$ (unweighted; Reichmuth *et al.*, 2016; Sills *et al.*, 2020). A bearded seal (*Erignathus barbatus*) in the same setup showed TTS to exposures between 191 and 195 dB re $1 \mu\text{Pa}^2 \text{ s}$ (Sills *et al.*, 2020). A third study (Kastelein *et al.*, 2018a) used pile driving noise as fatiguing sound and measured an unweighted TTS onset threshold of 193 dB re $1 \mu\text{Pa}^2 \text{ s}$ in two harbor seals. PCW-weighted exposure levels were provided for the bearded seal by Sills *et al.* (2020) but not for the two other studies. However, as decade frequency spectra are available for both of the studies, a PCW frequency weighting could be performed, as described in Sec. III (Fig. 2). The total energy of the fatiguing sound was calculated from the spectra by summing the individual decade bands, thereby calculating the difference between the weighted and unweighted thresholds. This difference and PCW-weighted thresholds are listed in Table I.

B. Harbor porpoise

Four studies with non-impulsive (narrowband) pulses are included in the data for Southall *et al.* (2019), including one study on finless porpoises (*Neophocoena phocaenoides*) in which all of the fatiguing stimuli produced considerable TTS (Popov *et al.*, 2011) and two studies with impulsive (broadband) sounds. More recent studies comprise 12 publications on non-impulsive sounds and 5 studies on impulsive sounds. All of the studies and TTS onset thresholds derived from these are listed in the Appendix.

1. Non-impulsive sounds

The auditory weighting function of Southall *et al.* (2019) for VHF-cetaceans is based on three data points. These are plotted in Fig. 3, together with the exposure function (inverted weighting function) and data points after 2015 from three individual porpoises. TTS onset thresholds for two finless porpoises (Popov *et al.*, 2011) are also included. These data points, however, not only come from a different species but are also based on downward extrapolation from substantial levels of TTS induced in the animals (20 dB TTS and above). Substantial uncertainty is, thus, associated with these data points, and they are included for completeness only.

Overall, there is a good agreement between TTS onset thresholds at lower frequencies (6.5 kHz and lower) and predictions from the VHF exposure function of Southall *et al.* (2019). At higher frequencies, one study (Schaffeld *et al.*, 2019) reported a TTS onset threshold at 14 kHz, which is more than 10 dB lower than the predictions, whereas several studies at frequencies from 16 to 88 kHz (Kastelein *et al.*, 2019a; Kastelein *et al.*, 2019d; Kastelein *et al.*, 2020a; Kastelein *et al.*, 2020d) reported TTS onset thresholds

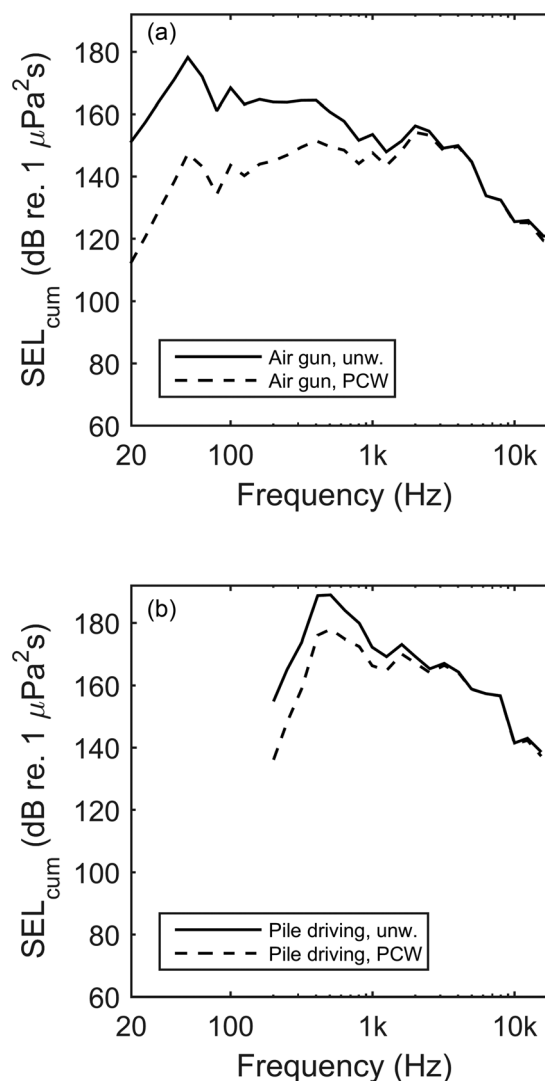


FIG. 2. The (a) unweighted and PCW-weighted decade spectrum of the loudest airgun pulse from Reichmuth *et al.* [2016, Fig. 2(c)] and (b) unweighted and PCW-weighted decade spectrum of the pile driving pulse used by Kastelein *et al.* [2018a, Fig. 1(a)], adjusted in amplitude to match the TTS onset threshold, are shown.

substantially higher than predicted, as much as nearly 40 dB. These TTS onset thresholds between 16 and 88 kHz are also substantially higher than the thresholds derived from experiments on finless porpoises (indicated by asterisks in Fig. 3) in the same frequency range.

2. Impulsive sounds

Fewer studies are available for porpoises with impulsive (broadband) sounds. A seminal study is that by Lucke *et al.* (2009), which showed that TTS, surprisingly, could be induced in a harbor porpoise by exposure to a single pulse from an airgun at a received unweighted (broadband) SEL of only 164 dB re $1 \mu\text{Pa}^2 \text{ s}$, adjusted to 163 dB re $1 \mu\text{Pa}^2 \text{ s}$ by Finneran (2015). Recently Lucke *et al.* (2020), in a reevaluation of the data from Lucke *et al.* (2009), provided VHF-weighted levels of the exposures used in the original study. From the relationship between unweighted and VHF-weighted

TABLE I. The TTS onset thresholds for phocid seals derived from studies with impulsive (broadband) sounds as fatiguing stimulus.

Reference	Sound	Pulses	Animal	TTS onset threshold (re $1 \mu\text{Pa}^2 \text{ s}$)		Included in Southall <i>et al.</i> (2019)
				Unweighted	Weighted	
Reichmuth <i>et al.</i> (2016)	Airgun	1	2 Ringed seals	>181 dB	>162 dB	No
		1	2 Spotted seals			
Kastelein <i>et al.</i> (2018a)	Pile driving	8280–16 560	2 Harbor seals	193 dB	183 dB	No
Sills <i>et al.</i> (2020)	Airgun	2–10	Bearded seal	191–195	167–171 dB	No
		1	Ringed seal	>180 dB	>161 dB	

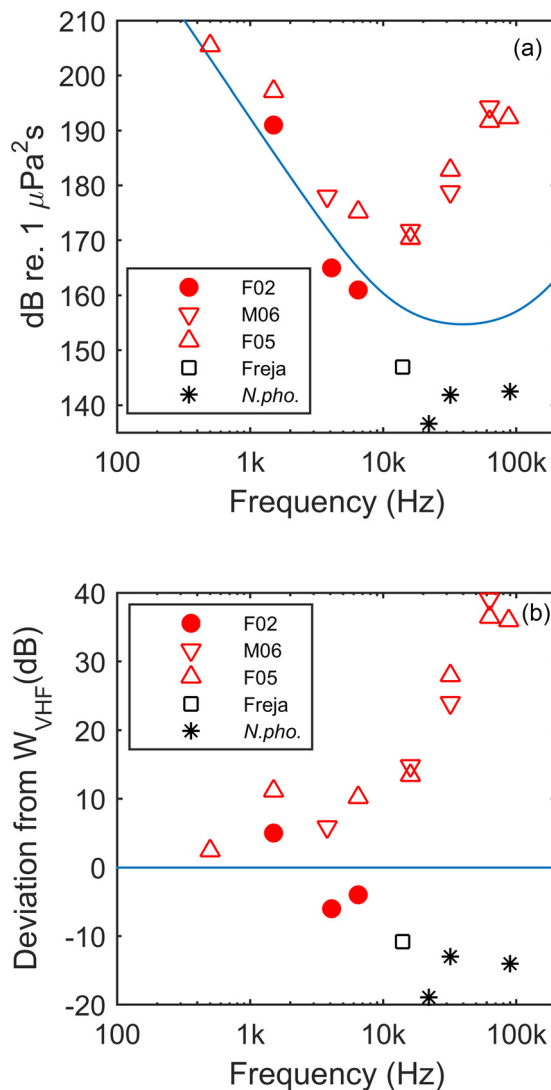


FIG. 3. (Color online) The (a) TTS onset thresholds for harbor porpoises are shown with different symbols indicating individual experimental subjects. The data points until 2015 (included in Southall *et al.*, 2019) are shown with filled symbols, and more recent data are shown with open symbols. The black symbols indicate that the animal was exposed for a shorter period (minutes) at a stationary position; the red symbols indicate a longer exposure (hours) to free-swimming animals. Three data points from finless porpoises (Popov *et al.*, 2011), indicated by asterisks (*), are also included. These points are associated with considerable uncertainty and included for reference only (see the text). (b) The same data as in (a) but normalized to the exposure function (blue line). See Table IV in the Appendix for details on individual experiments.

levels of the air gun pulse (Table II in Lucke *et al.*, 2020), a weighted threshold for the 2009 experiment was found by a linear regression between weighted and unweighted levels (see the supplementary material³). The VHF-weighted TTS onset threshold from Lucke *et al.* (2009) was thereby found to be 138 dB re $1 \mu\text{Pa}^2 \text{ s}$.

Since Finneran (2015), several other studies using impulsive sounds on porpoises have appeared. Kastelein *et al.* (2015a) measured TTS in a porpoise after exposure to a 1 h sequence of pile driving pulses and reported a threshold of 180 dB re $1 \mu\text{Pa}^2 \text{ s}$, unweighted, cumulated over all of the pulses. A subsequent study with the same animal and fatiguing sounds but with variable exposure duration (Kastelein *et al.*, 2016) reported a slightly lower threshold for TTS: 175 dB re $1 \mu\text{Pa}^2 \text{ s}$, unweighted. Two additional studies on the same animal (Kastelein *et al.*, 2017c; Kastelein *et al.*, 2020f) with air-gun pulses as fatiguing sounds reported unweighted TTS thresholds of 191 and 199 dB re $1 \mu\text{Pa}^2 \text{ s}$, respectively.

As the frequency spectra of the signals from the studies by Kastelein *et al.* (2015a), Kastelein *et al.* (2016), Kastelein *et al.* (2017b), and Kastelein *et al.* (2020f) are known, it is possible to weight them with the VHF weighting function as was done for the harbor seal results (Fig. 4). All of the weighted and unweighted thresholds are listed in Table II.

V. DISCUSSION

The weighting functions derived by Southall *et al.* (2019) were based on limited empirical data, except for the HF-cetaceans, where substantial data were available from bottlenose dolphins (*Tursiops truncatus*) and beluga (*Delphinapterus leucas*). This, in concert with the recognition that collection of new data will always be ahead of integrative reviews and generalizing synthesis, Southall *et al.* (2007) and Southall *et al.* (2019) anticipated and encouraged revision of their recommendations in light of the emerging new data. Pointing to discrepancies between predictions of their work and data not available in 2015 is, thus, not a critique of the work already performed but simply an extension of their work along the very same lines laid out in their reviews.

For harbor seals, only two data points from two different animals were used to establish the recommendations of Southall *et al.* (2019), and for harbor porpoises, only three data points, all from the same individual, were available. Inclusion of the results from a significant number of new

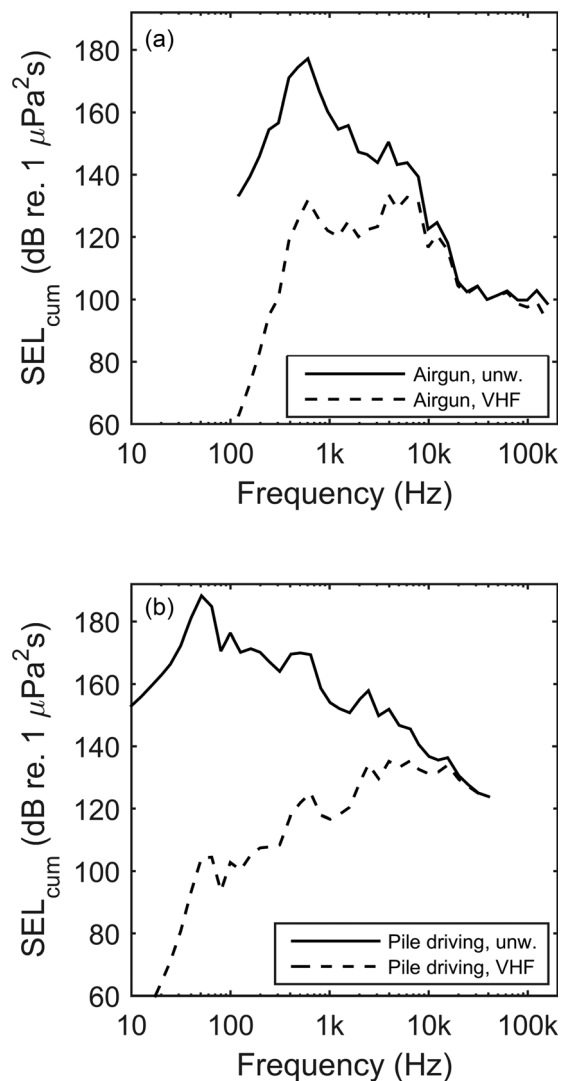


FIG. 4. The decade SEL of impulsive sounds used in the TTS experiments on porpoises. The (a) air gun sound used by Kastelein *et al.* (2017c) and Kastelein *et al.* (2020f) and (b) pile driving sound used by Kastelein *et al.* (2015a) and Kastelein *et al.* (2017c) are depicted. The solid lines indicate unweighted levels adjusted to a total SEL equal to the TTS threshold of the experiments and broken lines indicate the same spectra weighted with the VHF-cetacean weighting function.

studies makes it possible to critically review the proposed weighting functions and generalized TTS onset thresholds proposed by Southall *et al.* (2019). Several systematic discrepancies between the predictions of Southall *et al.* (2019) and new experimental data are observed in some cases and

also a good agreement between the predictions and new results were observed in other cases. These findings are summarized in Table III.

A. Thresholds for impulsive sounds

Southall *et al.* (2019) provided weighted TTS onset thresholds for impulsive sounds for phocid seals and VHF-cetaceans of 170 dB re $1 \mu\text{Pa}^2 \text{ s}$ and 140 dB re $1 \mu\text{Pa}^2 \text{ s}$, respectively. Neither of these two thresholds were based on empirical evidence, but they were based largely on extrapolation of the results from TTS onset thresholds for non-impulsive sounds and available evidence from bottlenose dolphins and belugas. For phocid seals and VHF-cetaceans, there are now data from experiments with airguns and pile driving noise as fatiguing sounds (Tables I and II, respectively).

The interpretation of the results with impulsive sounds as fatiguing stimuli is difficult, especially the transfer from experimental settings to full-scale exposures on free-swimming animals—and is associated with significant uncertainty. To reach cumulated SELs sufficient to induce TTS, one can either use the actual source (possible with small air guns and impossible with pile driving noise) or a recorded signal, which is played back through an adequate transducer. In both cases, it is difficult to replicate the full frequency spectrum of the actual source, either because the frequency response of the transducer does not cover the lowest part of the spectrum (see, for example, Fig. 5 in Kastelein *et al.*, 2013b) or because of problems with propagation of the lowest frequencies in the shallow waters typical of experimental settings (see, for example, Lucke *et al.*, 2020).

Bearing these caveats in mind, the results from porpoises are remarkably consistent across experimental paradigms and individuals and cluster well around the 140 dB re $1 \mu\text{Pa}^2 \text{ s}$ threshold proposed by Southall *et al.* (2019), thus, lending substantial support to this weighted threshold, at least for pile driving and airgun sounds. The results from phocid seals are somewhat more scattered and TTS onset thresholds range from 167 to 183 dB re $1 \mu\text{Pa}^2 \text{ s}$, measured across four different species and in two different facilities. The scatter in the results can possibly be attributed to differences between the stimuli (airguns vs playback of pile driving noise), differences between experimental facilities and protocols, or genuine differences between the four different species or seven different individuals studied. While it likely

TABLE II. Thresholds for inducing TTS by impulsive sounds in harbor porpoises.

Reference	Sound	Animal	Weighting (dB)	TTS threshold (weighted)	Included in Southall <i>et al.</i> (2019)
Porpoises—I-type sounds					
Lucke <i>et al.</i> (2009)	Airgun	Freja	25	138 dB re $1 \mu\text{Pa}^2 \text{ s}$	Yes
Kastelein <i>et al.</i> (2015a)	Pile driving	M02	40	>140 dB re $1 \mu\text{Pa}^2 \text{ s}$	Yes
Kastelein <i>et al.</i> (2016)	Pile driving	M02	40	135 dB re $1 \mu\text{Pa}^2 \text{ s}$	No
Kastelein <i>et al.</i> (2017c)	Airgun	M06	47	144 dB re $1 \mu\text{Pa}^2 \text{ s}$	No
Kastelein <i>et al.</i> (2020f)	Airgun	M06	47	>143–149 dB re $1 \mu\text{Pa}^2 \text{ s}$	No

TABLE III. The summary of findings in comparing the proposed generalized (weighted) TTS onset thresholds for phocid seals and VHF-cetaceans (Southall *et al.*, 2019) to recent empirical data that were not available to Southall *et al.* (2019).

Phocid seals			VHF-cetaceans	
Impulsive sounds	Agreement but large scatter in empirical data		Good agreement	
Non-impulsive sounds	Below 3 kHz	Measured thresholds substantially higher than the prediction below 3 kHz; requires further investigation.	Below 10 kHz	Good agreement
	3–20 kHz	Good agreement	10–20 kHz	Agreement but substantial scatter of results
	Above 20 kHz	Measured thresholds consistently lower than predictions; weighting function may need adjustment	above 20 kHz	Measured thresholds substantially higher than the prediction; requires further investigation

will require additional experiments to identify the source of variation, it is worth noting that the TTS onset threshold measured in the bearded seal exposed to ten or fewer impulses is within 3 dB of the current threshold from Southall *et al.* (2019), whereas the threshold for the free-swimming harbor seal, exposed to several thousand weaker pile driving pulses, is more than 20 dB higher than the TTS onset threshold of Southall *et al.* (2019). This difference is consistent with an overestimation of the received SEL in the case of the free-swimming seal. The precautionary approach to setting TTS onset thresholds would, therefore, be to retain the current threshold and at the same time, test the validity of the low susceptibility to TTS found by Kastelein *et al.* (2018a) through new experiments.

B. Phocid seals: Non-impulsive sounds

The current phocid weighting function in water is based on two data points in the frequency range 3–5 kHz. Two newer data points at 8 and 16 kHz are consistent with the thresholds predicted from the exposure function, lending support to the weighting function in this frequency range. Two additional experiments at higher frequencies (32 and 40 kHz) resulted in thresholds that were 7–10 dB lower than the prediction of the exposure function, indicating a higher than predicted sensitivity to TTS in the two tested harbor seals. This leads to the conclusion that the shape of the weighting function should likely be revisited for frequencies above 20 kHz and adjusted to better reflect the new data.

Additional data are also available at frequencies below 3 kHz from the same two seals that have provided most of the other data points. At frequencies of 0.5, 1, and 2 kHz, predictions of TTS onset thresholds are substantially higher than those predicted from the exposure function. For 500 Hz, no significant TTS at exposures 20 dB above the predicted threshold was observed. As the seals were reported to spend between 17% and 73% of the exposure time (between 1 and 6 h) with the head at the surface, it is possible that the cumulated SEL that the seals actually received was well below the level estimated from the sound field measurements deeper in the pool. The exposure was quantified by a meticulous mapping of the sound pressure levels at different locations and depths in the tank (in the absence of the seals) and from these, an average exposure

was estimated. Such an estimate, however, relies critically on the mean being representative of the sound pressures that were actually present at the location of the seal's ear. The details of sound reception under water are still largely unknown in seals, but sound in water likely enters the head through an acoustic window below the outer meatus (Møhl and Ronald, 1975; see also Kastelein *et al.*, 2018b). If the seal swims very close to the surface, the sound pressure at the acoustic window of the seal is likely to be well below the level predicted from measurements made at 0.5 m depth (the shallowest depth of measurements in the 2 m deep pool) due to pressure release from the surface and destructive interference by reflections from the surface (Lloyd's mirror effect). Because these effects are more pronounced at low frequencies due to the longer wavelengths, this could explain why the largest discrepancy from the expectations occurs at the lowest frequencies. Whether this is the case or the seals are in fact less prone to TTS than predicted at low frequencies can be tested with an animal exposed to noise while stationary in a calibrated sound field under water (as performed in the studies by Kastak *et al.*, 2005; Kastak *et al.*, 2008; Reichmuth *et al.*, 2016; and Sills *et al.*, 2020) or by direct measurements of the sound exposure of the swimming seals, for example, by monitoring the sound level directly on the side of the seal's head with a small hydrophone attached to a suitable recorder on the back of the seal.

C. VHF-cetaceans: Non-impulsive sounds

The current VHF weighting function is based on three data points between 1.4 and 7 kHz, all of which were obtained from the same animal. A substantial number of additional data points have become available since 2015 on three other individuals and at higher and lower frequencies. For frequencies between 500 Hz and 10 kHz, there is a good correspondence between the new experimental data and predictions of the exposure function. In the intermediate range, 10–20 kHz, there are now two studies on three different animals with substantial scatter in the TTS onset thresholds. The lowest threshold was measured with the auditory evoked potentials (AEP) technique at 14 kHz (Schaffeld *et al.*, 2019), and this threshold is nearly 30 dB lower than the least sensitive of two animals tested with behavioral methods at 16 kHz (Kastelein *et al.*, 2019d). Although the

average of the TTS onset thresholds of these two experiments is close to the predicted threshold from the VHF exposure function, the source of the large variation should be further investigated. In particular, it needs to be understood if the discrepancies relate to evoked potential vs behavioral methodology: The large difference may possibly be explained by the different experimental protocols as TTS is known for bottlenose dolphins to occur at lower exposure levels when hearing thresholds are measured by evoked potentials rather than if measured by behavioral techniques (Finneran *et al.*, 2007). Another possible explanation is the difference in the duration of the fatiguing noise in the two studies: 1 h of low-intensity noise vs 0.5 s of high-intensity noise (Kastelein *et al.*, 2019d; Schaffeld *et al.*, 2019, respectively), where the short duration exposure is more likely to generate a TTS for the same summed SEL as the long exposure.

Above 20 kHz, the measured TTS onset thresholds for harbor porpoises are consistently higher than the predicted thresholds from the VHF exposure function, by about 35 dB for the highest frequencies (64 and 88 kHz), and even higher than the extrapolated TTS onset thresholds for finless porpoises in the same frequency range. A difference in the TTS onset threshold of 35 dB reflects an expected comparison between one pulse with the intensity predicted from the exposure function to elicit TTS and an exposure more than 3000 times longer actually being required. Such a large deviation between predictions and measurements at relatively high frequencies is puzzling and deserves careful scrutiny in future experiments. As noted by Kastelein *et al.* (2020d), it is known that dolphins and porpoises can reduce their hearing sensitivity by up to 40 dB when anticipating loud sounds in the frequency range 20–80 kHz (Nachtigall and Supin, 2014; Nachtigall *et al.*, 2016; Finneran, 2018), which can potentially explain the discrepancies between the prediction and measurements in full or in part. Whether the ability of porpoises to raise their hearing threshold is larger at higher frequencies is unknown and should be tested by experiments. If possible, such experiments should also address the large discrepancy between the results from harbor porpoises and the results of Popov *et al.* (2011) on finless porpoises. From a regulatory point of view, a precautionary approach would be to retain the current VHF weighting function until the source of the discrepancies between the results from harbor porpoises and finless porpoises have been identified. At the same time, however, it should be explored whether the possible reduced risk of TTS and PTS following noise exposure—if the exposure is anticipated by the animal—could be exploited in mitigation of the impact. Such mitigation could be in the form of warning sounds immediately before loud noise emissions (Nachtigall and Supin, 2013).

All of the available data between 16 and 88 kHz were obtained from the same two porpoises in the same facility and with the same experimental protocol. As the two animals are consistent in their responses and have shown normal hearing in other experiments (Kastelein *et al.*, 2017b), it

appears unlikely that they are both atypical in their susceptibility to TTS. This, again, points to the experimental protocol, where animals are free to swim around in the pool during exposure as a possible explanation as to why the exposure of the animals might be underestimated, which, in turn, would lead to the higher than expected observed TTS onset threshold. It is noteworthy, however, that the same noise exposure protocol resulted in lower than expected TTS onset thresholds at 32 and 40 kHz for seals. In any case, it would be straightforward to test for a possible effect of the protocol by conducting experiments with a porpoise trained to station in a fixed position while exposed to narrowband noise at frequencies in the range 16–88 kHz. If the exposure function of Southall *et al.* (2019) is correct, an exposure to, for example, a 32 kHz fatiguing noise of 1 s at 160 dB re 1 μ Pa (SEL = 160 dB re 1 μ Pa² s) should induce a small amount of TTS at 50 kHz, half an octave higher. In contrast, according to the results of Kastelein *et al.* (2019a), a continuous exposure of the same frequency for 2 min (SEL = 181 dB re 1 μ Pa² s) would be required to induce a minimum TTS. Alternatively, the received noise during exposure of a free-swimming animal could be measured directly, as suggested for the seals, by equipping the porpoise with a sound dosimeter during long duration exposures to fatiguing noise.

VI. CONSEQUENCES FOR LEGISLATION

Substantial interest from regulatory bodies and other stakeholders surrounds the question of estimating generalized, weighted thresholds for TTS onset in marine mammals as they form the basis of legislation and regulation of noise-generating activities in many countries. The present review of available data leads to conclusions regarding impact on phocid seals and harbor porpoises⁴ from exposure to some of the most common types of noise sources: pile driving, airguns, sonars, and acoustic deterrent devices.

A. Pile driving, airguns, and other impulsive sounds

The TTS onset thresholds proposed by Southall *et al.* (2019) for impulsive (broadband) sounds are in good agreement with direct experimental results for pile driving playback and airgun sounds as fatiguing stimuli, which lends substantial support for the use of the suggested thresholds in regulation of the impact from pile driving and seismic surveys. No experimental results are available for other loud impulsive sounds, such as those generated by sparkers and other geoacoustic equipment, but until such data may become available, it seems reasonable and precautionary to conclude that the current thresholds would be applicable to these sources as well. Shock waves from explosions, however, are acoustically very different from the other impulsive sounds and criteria other than weighted SEL may be more appropriate, such as peak pressure or acoustic impulse.⁵ See Southall *et al.* (2019) and Lance and Bass (2015) for further discussion.

B. Low- and mid-frequency sonars

Low- and mid-frequency sonars, all in the range below 10 kHz, have been the subject of several of the studies reviewed above due to their high relevance to the use and possible regulation of military sonar exercises. The updated results for this group of non-impulsive sounds are very different in seals and harbor porpoises. Whereas there is strong support for the use of the VHF-weighted threshold proposed by Southall *et al.* (2019) for harbor porpoises (153 dB re 1 $\mu\text{Pa}^2\text{s}$), there is substantial discrepancy between the predictions and experimental results for seals. However, as the new experimental data indicate a lesser sensitivity to low-frequency sounds than the current criteria, the current criteria are precautionary as they are.

C. Acoustic deterrent devices and other high frequency sources

The results from seals appear to indicate a higher sensitivity to TTS at high frequencies than predicted by Southall *et al.* (2019), lending support to a revision of the phocid weighting function for frequencies above 20 kHz, making the criteria more precautionary for high frequency sounds. The situation is more complex for harbor porpoises when it comes to non-impulsive sounds above 20 kHz as there are major and systematical deviances between the predictions and experimental results. However, sound exposures, if weighted by the current VHF weighting function, will overestimate impact and thereby be precautionary.

VII. CONCLUSION

The initial (Southall *et al.*, 2007) and recent recommendations (Southall *et al.*, 2019) stressed the need for regular data driven revisions of the weighting functions and thresholds if required. The present review of new experimental data for porpoises (VHF-cetaceans) and phocid seals has highlighted the importance of such an iterative process.

Despite significant discrepancies between newer data and the existing weighting functions, especially at the higher and lower edges, the current thresholds and weighting functions for VHF-cetaceans and phocid carnivores are still precautionary and, therefore, if anything, will tend to overestimate impact in assessments. The only exception is for narrowband signals above 20 kHz for phocid seals, where the impact may be underestimated and a revision of the PCW weighting function is warranted. Most importantly, however, is that the thresholds for onset of TTS for pile driving noise, seismic air guns, and military low- and mid-frequency sonars are well supported by the experimental evidence that has become available after the current criteria were established. These three sources of underwater sound are among the most important anthropogenic sources from a regulatory viewpoint.

Substantial uncertainties remain when it comes to the impact of low-frequency noise exposure in seals and high frequency noise exposure in porpoises. The observed discrepancies between predicted and measured TTS onset thresholds can only be resolved through new and dedicated experiments.

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APPENDIX

The results of all studies included in this review are summarized in Table IV.

TABLE IV. All available data for the TTS in harbor porpoises, harbor seals, and other closely related species are shown; the recent studies that are not included in the current criteria (Southall *et al.*, 2019) are indicated in the last column.

Reference	Species	Fatiguing sound	Individual(s)	TTS threshold (unweighted)	Included in Finneran (2015)
Phocid seals—Impulsive sounds					
Reichmuth <i>et al.</i> (2016)	Spotted seal	Airgun at station	Tunu	>181 dB SEL	No
			Amak	>181 dB SEL	
	Ringed seal		Natchek	>181 dB SEL	
			Nayak	>181 dB SEL	
Kastelein <i>et al.</i> (2018a)	Harbor seal	Pile driving	F01	193 dB SEL	No
			F02	193 dB SEL	
Sills <i>et al.</i> (2020)	Bearded seal	Airgun at station	Noatak	191–195 dB SEL	No
	Ringed seal		Nayak	>180 dB SEL	
Phocid seals—Non-impulsive sounds					
Kastak <i>et al.</i> (1999)	Harbor seal	20 min octave band noise at 500 Hz, 1 kHz, and 2 kHz	Sprouts	2–9 dB of TTS at 60 dB above hearing threshold	No

TABLE IV. (Continued.)

Reference	Species	Fatiguing sound	Individual(s)	TTS threshold (unweighted)	Included in Finneran (2015)
Kastak <i>et al.</i> (2005)	Harbor seal	2.5 kHz octave band noise at station, up to 50 min duration	Sprouts	183 dB SEL	Yes
Kastak <i>et al.</i> (2008)	Harbor seal	4.1 kHz, 1 min pure tone	Sprouts	7–10 dB PTS at 202 dB SEL	Yes
Kastelein <i>et al.</i> (2012a)	Harbor seal	4 kHz octave-band noise, free-swimming, up to 4 h	F01	180 dB SEL	Yes
			F02	183 dB SEL	
Kastelein <i>et al.</i> (2013a)	Harbor seal	60 min of 4 kHz octave-band noise	F01	44 dB TTS at 199 dB SEL	Yes
			F02		
Kastelein <i>et al.</i> (2019c)	Harbor seal	60 min of a 6.5 kHz pure tone	F01	186 dB SEL	No
			F02	179 dB SEL	
Kastelein <i>et al.</i> (2019b)	Harbor seal	60 min of 16 kHz 1/6 octave band noise	F01	190 dB SEL	No
			F02	181 dB SEL	
Kastelein <i>et al.</i> (2020e)	Harbor seal	60 min of 32 kHz 1/6 octave band noise	F01	181 dB SEL	No
			F02	177 dB SEL	
Kastelein <i>et al.</i> (2020g)	Harbor seal	60 min of 40 kHz 1/6 octave band noise	F01	182 dB SEL	No
			F02	180 dB SEL	
Kastelein <i>et al.</i> (2020c)	Harbor seal	0.5 kHz 1/6 octave band noise, up to 6 h	F01	>211 dB SEL	No
			F02	>211 dB SEL	
		1 kHz 1/6 octave band noise, up to 6 h			
		2 kHz 1/6 octave band noise, up to 4 h	F01	211 dB SEL	
			F02	207 dB SEL	
			F01	226 dB SEL	
			F02	199 dB SEL	
Porpoises—Impulsive sounds					
Lucke <i>et al.</i> (2009)	Harbor porpoise	Single airgun pulse	Freja	164 dB SEL	Yes
Kastelein <i>et al.</i> (2015a)	Harbor porpoise	1 h pile driving playback	M02	180 dB SEL	Yes
Kastelein <i>et al.</i> (2016)	Harbor porpoise	0.25–6 h pile driving playback	M02	175 dB SEL	No
Kastelein <i>et al.</i> (2017c)	Harbor porpoise	20 airgun shots	M06	191 dB SEL	No
Kastelein <i>et al.</i> (2020f)	Harbor porpoise	Airgun	M06	>199 dB SEL	No
Lucke <i>et al.</i> (2020)	Harbor porpoise	Single airgun pulse ^a	Freja	163 dB SEL	
Porpoises—Non-impulsive sounds					
Popov <i>et al.</i> (2011)	Finless porpoise	20–100 kHz half-octave band noise, up to 30 min	Male and female	18–45 dB of TTS; lowest exposure 163 dB SEL	Yes ^b
Kastelein <i>et al.</i> (2012b)	Harbor porpoise	4 kHz octave band noise, up to 4 h	M02	164.5 dB SEL	Yes
Kastelein <i>et al.</i> (2014a)	Harbor porpoise	1–2 kHz sweep, 100% duty cycle, up to 4 h	M02	191 dB SEL	Yes
Kastelein <i>et al.</i> (2014b)	Harbor porpoise	6.5 kHz pure tone, 1 h	M02	161 dB SEL	Yes
Kastelein <i>et al.</i> (2015b)	Harbor porpoise	6–7 kHz sweep, 200 s	M02	180 dB SEL	No
Kastelein <i>et al.</i> (2017a)	Harbor porpoise	3.5–4.1 kHz FM sonar signal, up to 60 min	M06	178 dB SEL	No
Kastelein <i>et al.</i> (2019a)	Harbor porpoise	32 kHz 1/6-octave band noise for 60 min	M06	179 dB SEL	No
			F05	183 dB SEL	
Kastelein <i>et al.</i> (2019d)	Harbor porpoise	16 kHz 1/6-octave band noise for 60 min	M06	172 dB SEL	No
			F05	170 dB SEL	
Schaffeld <i>et al.</i> (2019)	Harbor porpoise	14 kHz pure tone, 0.5 s	Freja	147 dB SEL	No
Kastelein <i>et al.</i> (2020a)	Harbor porpoise	63 kHz 1/6-octave band noise for 60 min	M06	194 dB SEL	No
			F05	192 dB SEL	
Kastelein <i>et al.</i> (2020b)	Harbor porpoise	1.5 kHz 1/6-octave band noise for 60 min	F06	197 dB SEL	No
		6.5 kHz pure tone for 60 min		175 dB SEL	
Kastelein <i>et al.</i> (2020d)	Harbor porpoise	88 kHz 1/6-octave band noise for 60 min	F05	192 dB SEL	No
Kastelein <i>et al.</i> (2021)	Harbor porpoise	500 Hz 1/6 octave band noise, up to 4 h	F05	205 dB SEL	No

^aPer the reevaluation of Lucke *et al.* (2009); see also the supplementary material (footnote 3).^bThis is not included in the fitting of the weighting function but is included in the review.

¹The terminology changed with Southall *et al.* (2019) and the VHF functional hearing group is referred to as the high frequency (HF) functional hearing group in earlier literature, including Southall *et al.* (2007) and National Marine Fisheries Service (2016, 2018).

²With the ISO (2017) standard for underwater acoustic terminology, the term decade is the preferred term over the commonly used term 1/3 octave, both meaning a frequency band 1/10 decade wide, equal to approximately 1/3 octave.

³See supplementary material at <https://www.scitation.org/doi/suppl/10.1121/10.0011560> for details on frequency weighting of the TTS onset threshold for airgun pulses by Lucke *et al.* (2009) and TTS measurements from individual studies.

⁴The VHF cetacean functional hearing group includes several, not closely related species of small odontocetes, but as the majority of reviewed experiments have been conducted on harbor porpoises, and only a few data is available from finless porpoises, it remains to be demonstrated to what degree the results apply to the other species of the group.

⁵The acoustic impulse is a combined measure of the peak pressure and the time the peak pressure is sustained (area below the first positive peak in the pressure time-signal).

- Dähne, M., Tougaard, J., Carstensen, J., Rose, A., and Nabe-Nielsen, J. (2017). "Bubble curtains attenuate noise from offshore wind farm construction and reduce temporary habitat loss for harbour porpoises," *Mar. Ecol. Prog. Ser.* **580**, 221–237.
- Danish Energy Agency (2016). *Guideline for Underwater Noise—Installation of Impact-Driven Piles* (Danish Ministry of Energy, Copenhagen).
- European Commission (2008). "Directive 2008/56/EC of the European Parliament and of the Council of 17 June 2008 establishing a framework for community action in the field of marine environmental policy (Marine Strategy Framework Directive)" (Brussels, Belgium).
- Finneran, J. J. (2015). "Noise-induced hearing loss in marine mammals: A review of temporary threshold shift studies from 1996 to 2015," *J. Acoust. Soc. Am.* **138**, 1702–1726.
- Finneran, J. J. (2018). "Conditioned attenuation of auditory brainstem responses in dolphins warned of an intense noise exposure: Temporal and spectral patterns," *J. Acoust. Soc. Am.* **143**, 795–810.
- Finneran, J. J., Schlundt, C. E., Branstetter, B. K., and Dear, R. L. (2007). "Assessing temporary threshold shift in a bottlenose dolphin (*Tursiops truncatus*) using multiple simultaneous auditory evoked potentials," *J. Acoust. Soc. Am.* **122**, 1249–1264.
- German Federal Ministry for the Environment and Nuclear Safety (2013). *Concept for Protection of Harbour Porpoises from Noise Impact from Offshore Wind Farms in the German North Sea (Schallschutzkonzept)* (German Federal Ministry for the Environment and Nuclear Safety, Berlin).
- Hastie, G., Merchant, N. D., Gotz, T., Russell, D. J. F., Thompson, P., and Janik, V. M. (2019). "Effects of impulsive noise on marine mammals: Investigating range-dependent risk," *Ecol. Appl.* **29**, e01906.
- Houser, D. S., Yost, W., Burkard, R., Finneran, J. J., Reichmuth, C., and Mulsow, J. (2017). "A review of the history, development and application of auditory weighting functions in humans and marine mammals," *J. Acoust. Soc. Am.* **141**, 1371–1413.
- ISO (2017). 18405, "Underwater acoustics—Terminology" (International Organization for Standardization, Geneva).
- Kastak, D., Mulsow, J., Ghoul, A., and Reichmuth, C. (2008). "Noise-induced permanent threshold shift in a harbor seal," *J. Acoust. Soc. Am.* **123**, 2986.
- Kastak, D., Schusterman, R. J., Southall, B. L., and Reichmuth, C. J. (1999). "Underwater temporary threshold shift induced by octave-band noise in three species of pinniped," *J. Acoust. Soc. Am.* **106**, 1142–1148.
- Kastak, D., Southall, B. L., Schusterman, R. J., and Kastak, C. R. (2005). "Underwater temporary threshold shift in pinnipeds: Effects of noise level and duration," *J. Acoust. Soc. Am.* **118**, 3154–3163.
- Kastelein, R. A., Cornelisse, S. A., Huijser, L. A. E., and Helder-Hoek, L. (2020a). "Temporary hearing threshold shift in harbor porpoises (*Phocoena phocoena*) due to one-sixth-octave noise bands at 63 kHz," *Aquat. Mamm.* **46**, 167–182.
- Kastelein, R. A., Gransier, R., and Hoek, L. (2013a). "Comparative temporary threshold shifts in a harbor porpoise and harbor seal, and severe shift in a seal (L)," *J. Acoust. Soc. Am.* **134**, 13–16.
- Kastelein, R. A., Gransier, R., Hoek, L., MacLeod, A., and Terhune, J. M. (2012a). "Hearing threshold shifts and recovery in harbor seals (*Phoca vitulina*) after octave-band noise exposure at 4 kHz," *J. Acoust. Soc. Am.* **132**, 2745–2761.
- Kastelein, R. A., Gransier, R., Hoek, L., and Olthuis, J. (2012b). "Temporary threshold shifts and recovery in a harbor porpoise (*Phocoena phocoena*) after octave-band noise at 4 kHz," *J. Acoust. Soc. Am.* **132**, 3525–3537.
- Kastelein, R. A., Gransier, R., Marijt, M. A. T., and Hoek, L. (2015a). "Hearing frequency thresholds of harbor porpoises (*Phocoena phocoena*) temporarily affected by played back offshore pile driving sounds," *J. Acoust. Soc. Am.* **137**, 556–564.
- Kastelein, R. A., Gransier, R., Schop, J., and Hoek, L. (2015b). "Effects of exposure to intermittent and continuous 6–7 kHz sonar sweeps on harbor porpoise (*Phocoena phocoena*) hearing," *J. Acoust. Soc. Am.* **137**, 1623–1633.
- Kastelein, R. A., Helder-Hoek, L., Cornelisse, S., Huijser, L. A. E., and Gransier, R. (2019a). "Temporary hearing threshold shift in harbor porpoises (*Phocoena phocoena*) due to one-sixth-octave noise band at 32 kHz," *Aquat. Mamm.* **45**, 549–562.
- Kastelein, R. A., Helder-Hoek, L., Cornelisse, S., Huijser, L. A. E., and Terhune, J. M. (2019b). "Temporary hearing threshold shift in harbor seals (*Phoca vitulina*) due to a one-sixth-octave noise band centered at 16 kHz," *J. Acoust. Soc. Am.* **146**, 3113–3122.
- Kastelein, R. A., Helder-Hoek, L., Cornelisse, S. A., Defiliet, L. N., and Huijser, L. A. E. (2020b). "Temporary threshold shift in a second harbor porpoise (*Phocoena phocoena*) after exposure to a one-sixth-octave noise band at 1.5 kHz and a 6.5 kHz continuous wave," *Aquat. Mamm.* **46**, 431–443.
- Kastelein, R. A., Helder-Hoek, L., Cornelisse, S. A., Defiliet, L. N., Huijser, L. A. E., and Gransier, R. (2021). "Temporary hearing threshold shift in a harbor porpoise (*Phocoena phocoena*) due to exposure to a continuous one-sixth-octave noise band centered at 0.5 kHz," *Aquat. Mamm.* **47**, 135–145.
- Kastelein, R. A., Helder-Hoek, L., Cornelisse, S. A., Defiliet, L. N., Huijser, L. A. E., and Terhune, J. M. (2020c). "Temporary hearing threshold shift in harbor seals (*Phoca vitulina*) due to one-sixth-octave noise bands centered at 0.5, 1, and 2 kHz," *J. Acoust. Soc. Am.* **148**, 3873–3885.
- Kastelein, R. A., Helder-Hoek, L., Cornelisse, S. A., Huijser, L. A. E., and Gransier, R. (2020d). "Temporary hearing threshold shift at ecologically relevant frequencies in a harbor porpoise (*Phocoena phocoena*) due to exposure to a noise band centered at 88.4 kHz," *Aquat. Mamm.* **46**, 444–453.
- Kastelein, R. A., Helder-Hoek, L., Cornelisse, S. A., Huijser, L. A. E., and Terhune, J. M. (2020e). "Temporary hearing threshold shift in harbor seals (*Phoca vitulina*) due to a one-sixth-octave noise band centered at 32 kHz," *J. Acoust. Soc. Am.* **147**, 1885–1896.
- Kastelein, R. A., Helder-Hoek, L., Cornelisse, S. A., von Benda-Beckmann, A. M., Lam, F.-P. A., de Jong, C. A. F., and Ketten, D. R. (2020f). "Lack of reproducibility of temporary hearing threshold shifts in a harbor porpoise after exposure to repeated airgun sounds," *J. Acoust. Soc. Am.* **148**, 556–565.
- Kastelein, R. A., Helder-Hoek, L., Covi, J., and Gransier, R. (2016). "Pile driving playback sounds and temporary threshold shift in harbor porpoises (*Phocoena phocoena*): Effect of exposure duration," *J. Acoust. Soc. Am.* **139**, 2842–2851.
- Kastelein, R. A., Helder-Hoek, L., and Gransier, R. (2019c). "Frequency of greatest temporary hearing threshold shift in harbor seals (*Phoca vitulina*) depends on fatiguing sound level," *J. Acoust. Soc. Am.* **145**, 1353–1362.
- Kastelein, R. A., Helder-Hoek, L., Kommeren, A., Covi, J., and Gransier, R. (2018a). "Effect of pile-driving sounds on harbor seal (*Phoca vitulina*) hearing," *J. Acoust. Soc. Am.* **143**, 3583–3594.
- Kastelein, R. A., Helder-Hoek, L., and Terhune, J. M. (2018b). "Hearing thresholds, for underwater sounds, of harbor seals (*Phoca vitulina*) at the water surface," *J. Acoust. Soc. Am.* **143**, 2554–2563.
- Kastelein, R. A., Helder-Hoek, L., and Van de Voorde, S. (2017a). "Effects of exposure to sonar playback sounds (3.5–4.1 kHz) on harbor porpoise (*Phocoena phocoena*) hearing," *J. Acoust. Soc. Am.* **142**, 1965–1975.
- Kastelein, R. A., Helder-Hoek, L., and Van de Voorde, S. (2017b). "Hearing thresholds of a male and a female harbor porpoise (*Phocoena phocoena*)," *J. Acoust. Soc. Am.* **142**, 1006–1010.

- Kastelein, R. A., Helder-Hoek, L., Van de Voorde, S., von Benda-Beckmann, A. M., Lam, F. A., Jansen, E., de Jong, C. A. F., and Ainslie, M. A. (2017c). "Temporary hearing threshold shift in a harbor porpoise (*Phocoena phocoena*) after exposure to multiple airgun sounds," *J. Acoust. Soc. Am.* **142**, 2430–2442.
- Kastelein, R. A., Helder-Hoek, L., van Kester, R., Huisman, R., and Gransier, R. (2019d). "Temporary hearing threshold shift in harbor porpoises (*Phocoena phocoena*) due to one-sixth octave noise band at 16 kHz," *Aquat. Mamm.* **45**, 280–292.
- Kastelein, R. A., Hoek, L., Gransier, R., Rambags, M., and Claves, N. (2014a). "Effect of level, duration, and inter-pulse interval of 1–2 kHz sonar signal exposures on harbor porpoise hearing," *J. Acoust. Soc. Am.* **136**, 412–422.
- Kastelein, R. A., Parlog, C., Helder-Hoek, L., Cornelisse, S. A., Huijser, L. A. E., and Terhune, J. M. (2020g). "Temporary hearing threshold shift in harbor seals (*Phoca vitulina*) due to a one-sixth-octave noise band centered at 40 kHz," *J. Acoust. Soc. Am.* **147**, 1966–1976.
- Kastelein, R. A., Schop, J., Gransier, R., and Hoek, L. (2014b). "Frequency of greatest temporary hearing threshold shift in harbor porpoises (*Phocoena phocoena*) depends on the noise level," *J. Acoust. Soc. Am.* **136**, 1410–1418.
- Kastelein, R. A., van Heerden, D., Gransier, R., and Hoek, L. (2013b). "Behavioral responses of a harbor porpoise (*Phocoena phocoena*) to playbacks of broadband pile driving sounds," *Mar. Env. Res.* **92**, 206–214.
- Lance, R. M., and Bass, C. R. (2015). "Underwater blast injury: A review of standards," *Diving Hyperb. Med.* **45**, 190–199.
- Lucke, K., Martin, S. B., and Racca, R. (2020). "Evaluating the predictive strength of underwater noise exposure criteria for marine mammals," *J. Acoust. Soc. Am.* **147**, 3985–3991.
- Lucke, K., Siebert, U., Lepper, P. A., and Blanchet, M.-A. (2009). "Temporary shift in masked hearing thresholds in a harbor porpoise (*Phocoena phocoena*) after exposure to seismic airgun stimuli," *J. Acoust. Soc. Am.* **125**, 4060–4070.
- Møhl, B., and Ronald, K. (1975). "The peripheral auditory system of the harp seal, *Pagophilus groenlandicus* (Erxleben, 1777)," *Rapp. P.-v. Réun. Cons. Int. Explor. Mer.* **169**, 516–523.
- Nachtigall, P. E., and Supin, A. Y. (2013). "A false killer whale reduces its hearing sensitivity when a loud sound is preceded by a warning," *J. Exp. Biol.* **216**, 3062–3070.
- Nachtigall, P. E., and Supin, A. Y. (2014). "Conditioned hearing sensitivity reduction in a bottlenose dolphin (*Tursiops truncatus*)," *J. Exp. Biol.* **217**, 2806–2813.
- Nachtigall, P. E., Supin, A. Y., Pacini, A. F., and Kastelein, R. A. (2016). "Conditioned hearing sensitivity change in the harbor porpoise (*Phocoena phocoena*)," *J. Acoust. Soc. Am.* **140**, 960–967.
- National Marine Fisheries Service (2016). *Technical Guidance for Assessing the Effects of Anthropogenic Sound on Marine Mammal Hearing: Underwater Thresholds for Onset of Permanent and Temporary Threshold Shifts*, NOAA Technical Memorandum NMFS-OPR-59 (Silver Spring, MD), p. 178.
- National Marine Fisheries Service (2018). *2018 Revision to: Technical Guidance for Assessing the Effects of Anthropogenic Sound on Marine Mammal Hearing (Version 2.0): Underwater Thresholds for Onset of Permanent and Temporary Threshold Shifts*, NOAA Technical Memorandum NMFS-OPR-59 (Silver Spring, MD), p. 167.
- Popov, V. V., Supin, A. Y., Wang, D., Wang, K., Dong, L., and Wang, S. (2011). "Noise-induced temporary threshold shift and recovery in Yangtze finless porpoises *Neophocaena phocaenoides asiatorientalis*," *J. Acoust. Soc. Am.* **130**, 574–584.
- Reichmuth, C., Ghoul, A., Sills, J. M., Rouse, A., and Southall, B. L. (2016). "Low-frequency temporary threshold shift not observed in spotted or ringed seals exposed to single air gun impulses," *J. Acoust. Soc. Am.* **140**, 2646–2658.
- Schaffeld, T., Ruser, A., Woelfing, B., Baltzer, J., Kristensen, J. H., Larsson, J., Schnitzler, J. G., and Siebert, U. (2019). "The use of seal scarers as a protective mitigation measure can induce hearing impairment in harbour porpoises," *J. Acoust. Soc. Am.* **146**, 4288–4297.
- Sills, J. M., Ruscher, B., Nichols, R., Southall, B. L., and Reichmuth, C. (2020). "Evaluating temporary threshold shift onset levels for impulsive noise in seals," *J. Acoust. Soc. Am.* **148**, 2973–2986.
- Southall, B. L. (2021). "Evolutions in marine mammal noise exposure criteria," *Acoust. Today* **17**, 52–60.
- Southall, B. L., Bowles, A. E., Ellison, W. T., Finneran, J. J., Gentry, R. L., Greene, C. R., Kastak, D., Ketten, D. R., Miller, J. H., Nachtigall, P. E., Richardson, W. J., Thomas, J. A., and Tyack, P. L. (2007). "Marine mammal noise exposure criteria," *Aquat. Mamm.* **33**, 411–414.
- Southall, B. L., Finneran, J. J., Reichmuth, C., Nachtigall, P. E., Ketten, D. R., Bowles, A. E., Ellison, W. T., Nowacek, D. P., and Tyack, P. L. (2019). "Marine mammal noise exposure criteria: Updated scientific recommendations for residual hearing effects," *Aquat. Mamm.* **45**, 125–232.
- Tougaard, J., and Beedholm, K. (2019). "Practical implementation of auditory time and frequency weighting in marine bioacoustics," *Appl. Acoust.* **145**, 137–143.
- Tougaard, J., and Dähne, M. (2017). "Why is auditory frequency weighting so important in regulation of underwater noise?," *J. Acoust. Soc. Am.* **142**, EL415–EL420.
- Tougaard, J., Wright, A. J., and Madsen, P. T. (2015). "Cetacean noise criteria revisited in the light of proposed exposure limits for harbour porpoises," *Mar. Poll. Bull.* **90**, 196–208.