Thresholds for noise induced hearing loss in marine mammals

Background note to revision of guidelines from the Danish Energy Agency

Scientific note from DCE – Danish Centre for Environment and Energy

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Data sheet

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1 Summary

The applicability of recent literature reviews, meta-analyses and new empirical data to Danish guidelines for mitigation of impact from pile driving was assessed.

For the purpose of assessment of risk of hearing loss to marine mammals, sounds are separated into **type-I sounds** (impulsive sounds sensu Southall et al. 2019) and **other sounds**. Type-I sounds are characterized by the following three criteria:

- Very fast onset, often, but not always, followed by a slower decay.
- Short duration, fraction of a second.
- Large bandwidth.

Some sounds fulfill two, but not all three conditions (typically narrow-bandwidth signals). These signals are referred to as **P-type sounds** (non-pulses sensu Southall et al 2007). The distinction between the different types is indistinct, but is still of importance because it is recognized that type-I sounds have greater potential to induce hearing loss than P-type and other sounds and therefore raises a need for separate exposure limits.

It is proposed to use the sound exposure level capable of inducing a small, but permanent loss of hearing (PTS, permanent threshold shift) as basis for assessment and regulation of impact on marine mammals. Thresholds for inducing PTS are extrapolated from empiric thresholds for inducing temporary threshold shifts (TTS). These criteria are in line with existing Danish recommendations (Skjellerup et al., 2015) and the most recent and thorough review of the empirical data (National Marine Fisheries Service, 2016; Southall et al., 2019). The choice is based on the following reasoning

- PTS is a permanent impact on individuals, whereas TTS lasts only minutes to hours.
- Large amounts of PTS is likely to affect the energetic status of animals and hence survival, and possibly ability to mate and nurse offspring
- The impact on energetic status from some hours of moderate hearing loss (TTS) is unlikely to be significant and unlikely to affect survival or reproduction.

With the possible exception of explosions, which are not covered here, the assessment of risk of PTS is based on cumulated sound exposure level (SEL), being the time-integral of the signal intensity, equal to the acoustic energy over the duration of the sound exposure.

Marine mammal hearing differs between species and within species also with frequency. The inter-species variation is handled by grouping of species into functional hearing groups. Four groups defined by Southall et al. (2019) are relevant for Danish waters:

- LF-cetaceans: Mysticete whales, including minke whale
- MF-cetaceans: Most odontocetes, including white-beaked dolphin and pilot whale.

- VHF-cetaceans: Narrow-band high-frequency odontocetes, including harbour porpoise
- Phocid seals: True seals, including harbour seal and grey seal.

For each hearing group, a weighting function was developed by National Marine Fisheries Service (2016) and Southall et al. (2019). In cases where empirical data on thresholds for inducing TTS in relevant species was available, the weighting curve was fitted to this data. For other groups, most notably the LF-cetaceans, the curve was constructed from theoretical considerations.

Based on the empirical data, National Marine Fisheries Service (2016) and Southall et al. (2019) derived exposure limits (thresholds) for TTS for I-type sounds and other sounds. From these thresholds, the exposure levels required to induce permanent hearing loss (PTS) was extrapolated in a precautionary way by adding 15 dB to the TTS-threshold for I-type sounds and 20 dB for other sounds. These thresholds were evaluated against recent new empirical data from harbour porpoises and harbour seals. Hence it is recommended that the thresholds proposed by Southall et al. (2019), appropriately frequency weighted and as given in Table 1.1 are used in the Danish guidelines for assessing impact from pile driving.

Table 1.1. Proposed exposure limits for marine mammals relevant to Danish waters. All values are expressed as sound exposure level, i.e. the time integral of acoustic intensity over the period of exposure (dB re. 1 μPa^{2}s), weighted by the appropriate auditory frequency weighting function. See main text for details on frequency weighting. Adapted from Southall et al. (2019).

Species	Frequency weighting	Type I-sounds		Other sounds	
		TTS	PTS	TTS	PTS
Harbour porpoise	VHF	140	155	153	173
White-beaked dolphin	HF	170	185	178	198
Minke whale	LF	168	183	179	199
Pilot whale[1]	HF	170	185	178	198
Harbour seal	PCW	170	185	181	201
Grey seal	PCW	170	185	181	201

[1] For now considered representative also for beaked whales (Ziphiidae, including northern bottlenose whale), but may change when data becomes available for this group.

2 Background

The existing guidelines for mitigation of impact from pile driving were based on advice from a working group (Skjellerup et al., 2015), which, in turn, based its advice on the most comprehensive review at the time (Southall et al., 2007), supplemented with review of more recent data on noise induced hearing loss in harbour seals and harbour porpoises. One of the topics discussed in the working group, but left unanswered, was the question of frequency weighting of sound measurements, to improve the quality of assessment of impact. It was concluded at the time that such a decision was beyond the capacity of the working group and that not enough information was available. However, since completion of the work by the working group, a number of new studies have been published, one of which (Kastelein et al., 2016) prompted a revision of thresholds in the Danish guidelines (Skjellerup and Tougaard, 2016) and another included a review of harbour porpoise data (Tougaard et al., 2015). A very large review of the available literature was undertaken in the US at the same time, which resulted in three key publications: a review of all available studies of noise induced hearing loss in marine mammals (Finneran, 2015); a proposed revised framework for assessment (National Marine Fisheries Service, 2016); and an update of the advice from the US expert group along the same lines (Southall et al., 2019).

This report summarizes the information in these recent documents, as well as additional experimental studies relevant for Danish settings, to provide background for an update and revision of the Danish guidelines for noise emission from pile driving. In particular is evaluated the exposure limits proposed by Southall et al. (2019) and National Marine Fisheries Service (2016), which in turn is based on review of available empirical data up to 2015 (Finneran, 2015). A substantial number of empirical studies have since become available and the results of these are evaluated against recommendations of Southall et al. (2019).

This review is only concerned with impact in the form of noise-inflicted hearing loss. A subsequent note will deal with behavioural reactions to pile driving sounds.

3 Definitions

Some useful definitions are provided below. Terminology follows ISO 18405 (ISO, 2014) as closely as possible.

a. Sound pressure and energy

Sound is pressure fluctuations around the ambient pressure and thus a function of time, *t*. In the following we denote this as *p(t).* In most contexts it is relevant to quantify the sound pressure level, using just the symbol *p*, which is found from the root-mean pressure-squared, computed over some interval T:

Equation 3.1

$$L_p = 20\log_{10}\left(\frac{\sqrt{\frac{\int p^2(t)dt}{T}}}{p_0}\right)$$

Where p_0 is the reference pressure, by convention 1 µPa for underwater sound. The unit of sound pressure level is thus dB re. 1 µPa.

The energy, *E*, of a sound of duration, τ, is measured in Joule/m² and can be computed[2] from the pressure signal, *p(t)*, as

Equation 3.2

$$E = \frac{\int_0^{\tau} p(t)^2 dt}{\rho c}$$

Where *ρc*, known as the acoustic impedance, is the product of the density of the medium (here: water), *ρ*, and the sound speed, *c*. More commonly used in relation to impact assessments, however, is the sound exposure level (SEL), expressed in dB as:

Equation 3.3

$$SEL = L_{E,p} = 10\log\int_0^{\tau}\frac{p^2(t)}{p_0^2}dt$$

Where *p(t)* is the instantaneous pressure around ambient at time, *t* of a signal of duration *τ* and p_0 is the reference pressure (1 µPa, in water). The unit of SEL is thus dB re. 1µPa²s. By use of this reference, the acoustic impedance of **Equation 3.2** cancels out in the calculations, and can be conveniently ignored. It is possible to show that this unit is indeed a unit of energy flux density, being proportional to J/m².

b. Instantaneous intensity vs. accumulated dose

Note that the units of sound pressure level (dB re. 1 µPa) and sound exposure level (dB re. 1 µPa²s) are different, as they express two entirely different physical properties (pressure vs. energy). When discussing effects of noise it is important to be aware of this distinction between the acute sound pressure level (L_p, expressed as dB re. 1 µPa) and the accumulated acoustic energy (SEL, expressed as dB re. 1µPa²s). A useful analogy comes from toxicology, where some substances are acutely toxic, in which case one is concerned only with the concentration of

[2] Strictly speaking, this equation is only valid for a plane, propagating sound wave, i.e. not too close to the source and not in a confined space. It is a good approximation as long as one is more than several times the wavelength away from the source and not more than a few wavelengths away from reflective surfaces.

the toxin in the air breathed or food ingested. Other substances accumulate in the body, in which case the total dose accumulated over time becomes important. In acoustics, there are impacts, such as behavioural reactions, where the best predictor of a response is the instantaneous[3] sound pressure level, adequately frequency weighted (Tougaard et al., 2015); whereas other impacts, most notably hearing threshold shifts (TTS and PTS), are better predicted by the accumulated (time-integrated) acoustic energy (Southall et al., 2019; Tougaard et al., 2015). This difference in how effects are best predicted, based either on the acute exposure (sound pressure level, L_p) or cumulated dose (sound exposure level, SEL), precludes defining a single threshold to cover all effects. Some long-term sound exposures at low levels, have limited behavioural effects, but do induce hearing threshold shifts (Kastelein et al., 2016), and certain transient sounds, which induce behavioural reactions, do not influence hearing thresholds. The impact of pile driving must therefore be assessed separately for behaviour and risk of injury (hearing loss). This note deals only with assessment of risk of hearing loss, whereas behavioural effects will be dealt with in a separate note.

c. Impulses, pulses and other sounds

Some confusion exists in the literature on the use of the terms "pulse" and "impulse" as characterisation of sound signals. The confusion is partly based in semantics, partly in the lack of clear definitions. What is important is that there is a group of acoustic signals with some shared characteristics that make them different from other sounds when it comes to the ability to inflict damage to biological tissue, including hearing organs. These characteristics include:

- Very fast onset (short rise-time from start to peak pressure), measured in milliseconds. The onset is often, but not always, followed by a slower decay.
- Short duration, typically not more than a second.
- Large bandwidth
- Low time bandwidth product[4]

It is not possible to provide more exact definitions than the list above, but it is helpful with some examples. Good examples of sources that produce signals with the above characteristics are underwater explosions, seismic air guns and percussive pile driving. These sounds are distinct from other short and powerful sounds, which may have some of the listed properties, but not all four. Good examples of sources producing such sounds that do not fulfil all conditions are sonars (less sharp onset, often narrow bandwidth or with frequency modulation resulting in a high time bandwidth product), seal scarers (long duration, narrow bandwidth (although often with strong harmonics[5]). These sounds lie on a continuum from the shock wave generated by an explosion as one extreme to continuous[6] noise from ships propellers etc. at the other extreme.

[3] With instantaneous should be understood the sound pressure level, L_p, calculated over a very short interval, comparable to the temporal integration time of the mammalian ear, roughly 0.1-0.2 s.

[4] The product of duration and bandwidth. For any given duration, there is a minimal (but not a maximal) bandwidth. So for very short signals, stating that the bandwidth is large, is often tautological. But in itself, a large bandwidth is not indicative of an impulsive sound.

[5] Some definitions of bandwidth will still render a sinusoidal sound with harmonics narrowband. Such definitions would be the more appropriate in classifying signals as impulsive.

[6] Continuous on a short time scale of minutes to hours. No sound is truly continuous outside textbooks.

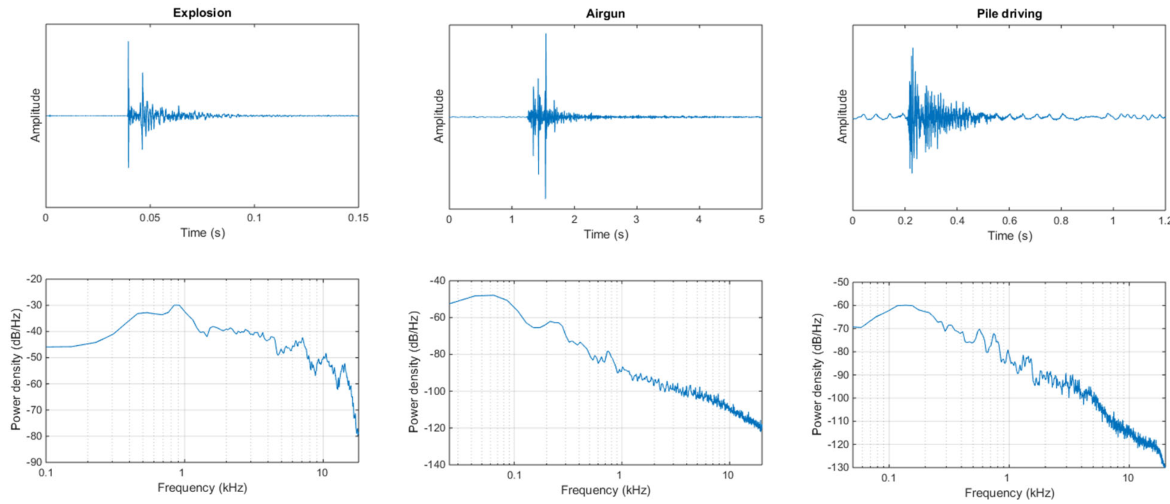


Figure 3.1. Examples of Impulsive (I-type) sounds, fulfilling the characteristics listed above.

It should be noted that long-range propagation of impulsive signals change the characteristics, through spectral filtering and stretching in time. Thus, at some distance from the source, an impulsive sound may lose one or more of the required characteristics and thus no longer fulfill conditions to be classified as impulsive. An example is shown in Figure 3.2, right: an airgun pulse, which has lost the sharp onset completely through multi-path propagation.

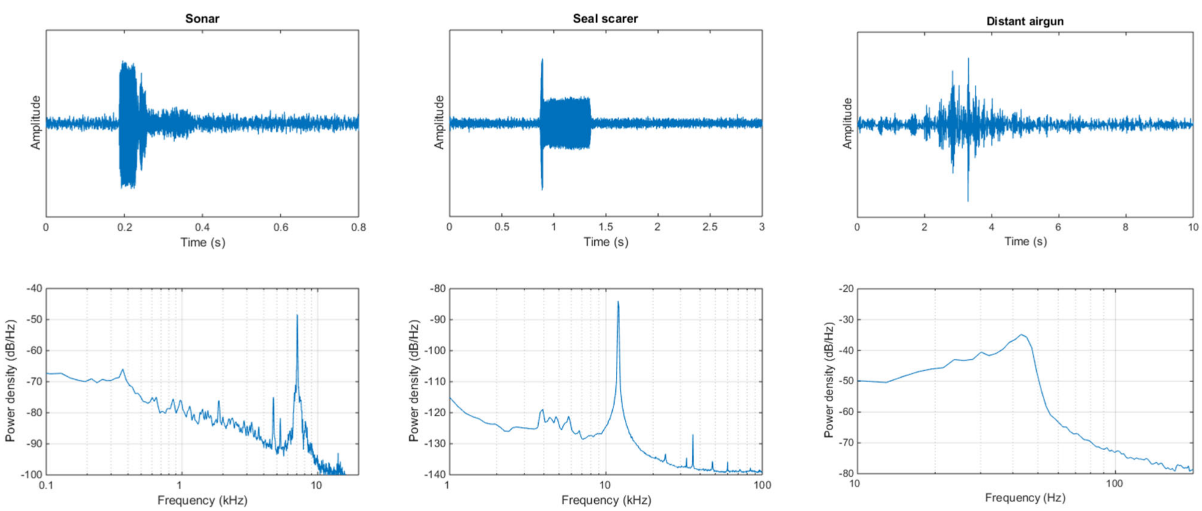


Figure 3.2. Examples of short sounds not fulfilling all criteria for I-type sounds and therefore referred to as P-type sounds. The sonar and seal scarer signals are short duration and have a sharp onset, but are narrow-band. The distant airgun sound (recorded more than 1000 km from the source) is longer and have lost the sharp onset.

The first group of sounds are referred to as impulses or impulsive sounds in some texts (National Marine Fisheries Service, 2016; Southall et al., 2019) and pulses in others (Southall, 2006); whereas the second group has been referred to as non-pulses (Southall 2006) and non-impulsive (National Marine Fisheries Service, 2016). While the term "impulsive sound" is probably the most consistent and most precise term, this term is also used in a broader sense in other contexts, such as in the EU Marine Strategy Framework Directive (European Commission, 2008), where it also applies to the second group of short signals (non-pulses, or non-impulses) and separates these two groups from the continuous sources, such as ships and offshore structures (bridges, platforms, renewable energy installations etc.).

Because it is important to retain the distinction between the two groups of short signals, but also to avoid confusion related to Marine Strategy Framework Directive literature, the term I-type sounds is proposed for the first group of sounds. If there is a need to refer to the other short and powerful signals and distinguish these from the I-type signals, the term P-type signals is proposed, leaving “other sounds” as the collective term for sounds that falls outside I and P types.

4 Noise-induced hearing loss as a proxy for injury

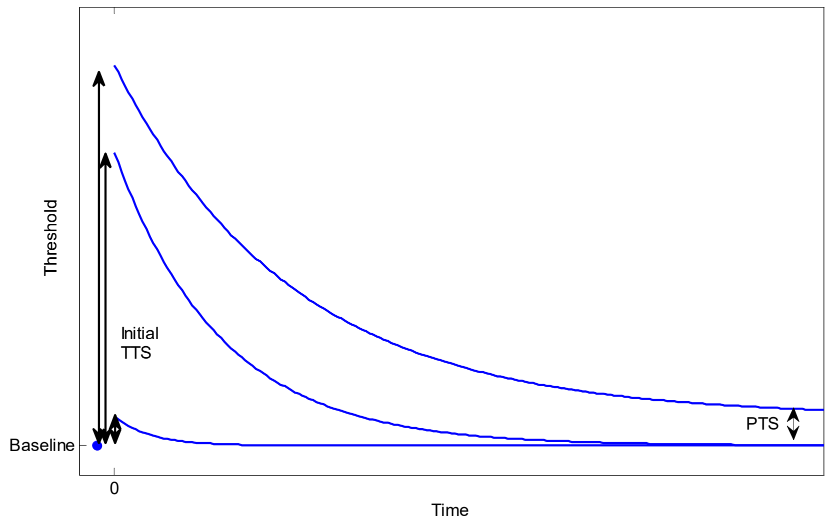
Underwater noise can impact marine mammals in different ways. The first dichotomy is between acute and direct damage (injury) caused by loud sound; and other effects of sound. The other effects can be as direct behavioural reactions to the noise or secondary effects through interference with perception of other sounds (masking) or through long-term effects on the physiology (elevated stress hormone levels, cardiovascular responses etc.). Very loud noise, maybe in reality limited to the shock wave from underwater explosions, is capable of causing direct damage to biological tissue (acoustic trauma), which can be fatal (Hill, 1978; Ketten, 1995; Lance and Bass, 2015; Lance et al., 2015; Lewis, 1996; Yelverton et al., 1973; Young, 1991). A number of studies have provided suggestions for exposure limits for marine mammals (Hill, 1978; Ketten, 1995; Yelverton et al., 1973; Young, 1991), based on direct experiments and studies of blast trauma in vertebrates. However, the consensus of Southall et al. (2007) was that a more precautionary threshold for injury was needed. As an alternative it was proposed to use the lowest sound level capable of inducing permanent hearing loss, known as permanent threshold shift (PTS). The rationale for this recommendation was (and is) that the ears, as specialized organs for sound reception, are likely to be the most sensitive tissue to noise exposure and therefore would be the tissue first affected by noise. Furthermore, while the exposure levels required to induce PTS cannot be measured in dedicated experiments, they can be extrapolated from experiments with inducted temporary threshold shift (TTS). TTS is the commonly observed reduction in hearing sensitivity following exposure to loud sound (rock concerts, gun shots etc.). TTS is fully reversible and can be induced in trained, captive animals under controlled conditions and is therefore readily measureable.

4.1 Temporary and permanent threshold shift

Temporary threshold shift, also referred to as “auditory fatigue”, is believed to be related to metabolic changes in the hair cells of the inner ear and/or higher neural pathways (Ryan et al., 2016). Recovery from small amounts of TTS is fast (minutes to hours) and complete, whereas large threshold shifts (40-50 dB) increases the risk that recovery is incomplete and therefore leaves the animal with a smaller, but permanent hearing loss (Permanent Threshold Shift, PTS).

A schematic illustration of the time course of TTS is shown in Figure 4.1. The amount of TTS immediately after end of the noise exposure is referred to as initial TTS. It expresses the amount by which the hearing threshold is elevated and is measured in dB. The larger the initial TTS, the longer the recovery period.

Figure 4.1. Schematic illustration of the time course in recovery of TTS. Zero on the time axis is the end of the noise. The threshold returns gradually to baseline level, except for very large amounts of initial TTS where a smaller, permanent shift (PTS) may persist. As the figure is schematic, there are no scales on the axes. Time axis is usually measured in hours to days, whereas the threshold shift is measured in tens of dB. From Skjellerup et al. (2015)



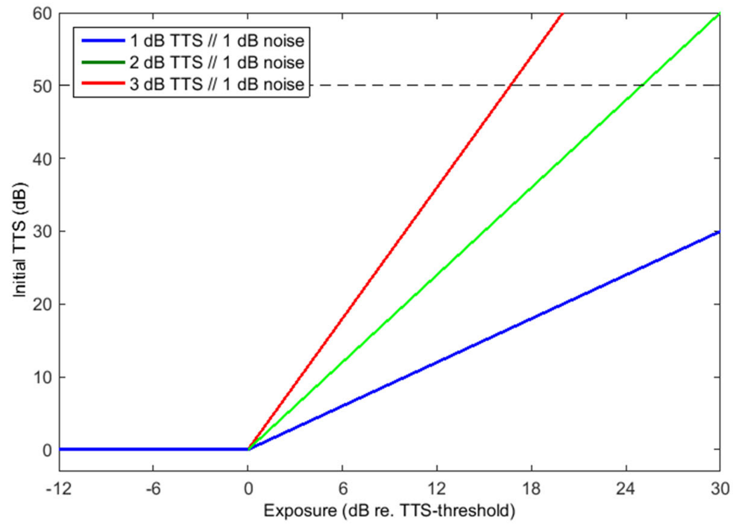
At higher levels of noise exposure, the hearing threshold does not recover fully, but leaves a smaller or larger amount of permanent threshold shift (PTS, see Figure 4.1). This permanent threshold shift is a result of damage to the sensory cells in the inner ear (Kujawa and Liberman, 2009). An initial TTS of 40 dB or higher is generally considered to constitute a significantly increased risk of generating a PTS (reviewed in National Marine Fisheries Service, 2016).

TTS and PTS is generally localised to frequencies around and immediately above the frequency range of the noise inducing the threshold shift. This means that TTS induced by low frequency noise, such as pile driving, typically only affects the hearing at low frequencies (Kastelein et al., 2013b).

4.2 Relationship between TTS and PTS

Thresholds for inducing TTS and PTS are thus central for assessment of risk of auditory injury. Deriving such thresholds has been the subject of a large effort from many sides (see reviews by Finneran, 2015; Southall et al., 2007; Southall et al., 2019). As PTS thresholds for ethical reasons cannot be measured by direct experiments, the agreed approach to estimate thresholds for PTS is by extrapolation from TTS thresholds to the noise exposure predicted to induce 40-50 dB of TTS and thus a significant risk of PTS. This extrapolation is not trivial, as it is complicated by the fact that the relationship between exposure and amount of initial TTS is not proportional (see review by Finneran, 2015). Thus, one dB of added noise above the threshold for inducing TTS can induce more than one dB of additional TTS (see Figure 4.2, note how the choice of slope has a very large influence on the estimated threshold for PTS). In Figure 4.2 the estimated PTS threshold is anywhere between 17 dB above the TTS threshold (red curve, 3 dB of TTS per added dB of noise) and 50 dB above the TTS threshold (blue curve, 1 dB of TTS per added dB of noise). The slope of the TTS growth-curve differs from experiment to experiment and slopes as high as 4 dB of TTS per dB of additional noise has been observed in a harbour porpoise (Lucke et al., 2009).

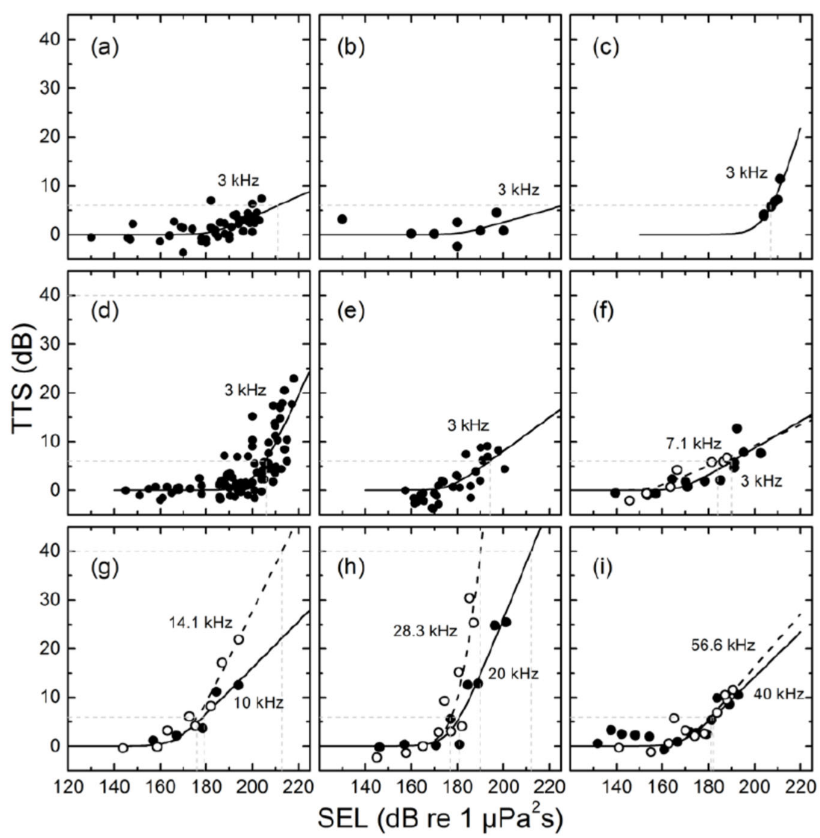
Figure 4.2. Schematic illustration of the growth of initial TTS with increasing noise exposure. Three different slopes are indicated. Note that the real curves are not necessarily linear. Broken line indicate threshold for inducing PTS, assumed in this figure to be at 50 dB initial TTS. From Skjellerup et al. (2015).



Based on compilation of results from all available data the growth of TTS with exposure level above TTS threshold was described for the different functional hearing groups by Southall et al. (2019). Example results are shown in Figure 4.3. These curves are used to extrapolate from TTS thresholds to PTS thresholds, based on observations from terrestrial mammals that a TTS of 40-50 dB increases the risk of a permanent threshold shift, PTS. Based on the slopes of the TTS growth curves for I-type and P-type sounds, the precautionary PTS thresholds were extrapolated by Southall et al. (2019) from the TTS thresholds as:

I-type sounds: $T_{PTS} = T_{TTS} + 15$ dB
P-type sounds: $T_{PTS} = T_{TTS} + 20$ dB

Figure 4.3. Examples of growth curves for TTS in HF cetaceans for nine different experiments. From National Marine Fisheries Service (2016).



4.3 Does TTS constitute an injury?

Some authors and regulatory bodies have argued that TTS in itself constitutes an injury and therefore should be the basis of regulation. This is most clearly expressed in the German legislation, the so-called '*Schallschutzkonzept*' (German Federal Ministry for the Environment and Nuclear Safety, 2013). This approach relies on a precautionary interpretation of the EU Habitats Directive (European Commission, 1992). The more common interpretation is that PTS constitutes a significant injury, whereas TTS does not. This is expressed for example in the US reviews and regulation (National Marine Fisheries Service, 2016; Southall et al., 2007; Southall et al., 2019) and has been adopted in regulation by other legislative bodies, including Denmark (Skjellerup et al., 2015) and the UK (JNCC, 2010). The choice of PTS as basis for regulation of impact is based on the following reasoning:

- PTS is a permanent impact on individuals.

- Large amounts of PTS, especially in the range of best hearing of the species, will impede the individual by affecting the ability to communicate with conspecifics, detect prey and predators, and to orient acoustically. This may in turn affect the energetic status of the individual and hence survival, and may affect the ability to mate and nurse offspring, thereby constituting a significant decrease in fitness.

- Small amounts of PTS (few dB, outside range of best hearing) is unlikely to affect the individual to a degree where survival and ability to mate and nurse offspring is affected significantly. In this sense a criterion for impact based on lowest detectable PTS (i.e. a few dB) is precautionary.

- TTS on the other hand is fully reversible (by definition) within minutes or hours. Severe TTS may last days, but in this case the risk for PTS is increased, which means that the impact is already covered.

- The impact on energetic status from some hours of moderate hearing loss (less than 15 dB, cf. criterion proposed by Southall et al., 2007; Southall et al., 2019) is unlikely to be significant and unlikely to affect survival or reproduction.

4.4 Equal energy hypothesis and cumulative SEL

A substantial effort has gone into quantifying sound levels required to elicit TTS in marine mammals. The initial experiments were primarily conducted on bottlenose dolphins, belugas and California sea lions (all reviewed by Southall et al., 2007), but recently also a large number of results are available from other species, most notably harbour porpoises (see comprehensive review by Finneran, 2015). The initial recommendations of Southall et al. (2007) reflected an uncertainty as to what single acoustic parameter best correlated with amount of TTS induced and resulted in a dual criterion: one expressed as instantaneous peak pressure and another as acoustic energy of the sound (integral of pressure squared over time, see below). In the reviews of Tougaard et al. (2015) and Finneran (2015) this uncertainty is no longer present and it is generally accepted that everything else being equal the amount of TTS correlates better with the acoustic energy than with the peak pressure. The acoustic energy is most often expressed as the sound exposure level (SEL, Equation 3.3 **abov**e). SEL equals the time integral of the sound intensity, which is the acoustic energy. For a signal of constant intensity, the energy is simply the duration times the intensity. Figure 4.4 illustrates four signals, which all have the same energy and thus according to the equal energy hypothesis should have the same ability to induce TTS.

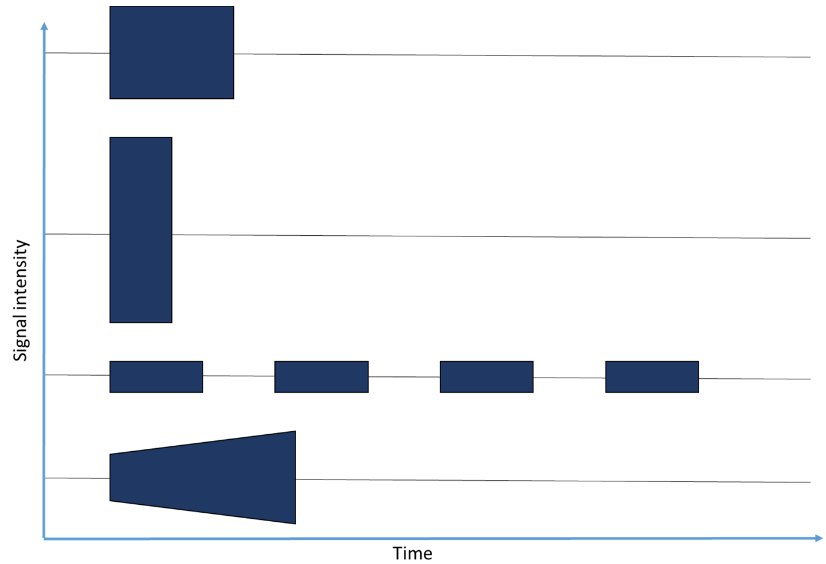


Figure 4.4. The equal energy hypothesis implies that all four examples of signals have the same ability to induce TTS, as they are of equal energy (the areas of the four signals are the same). It thus does not matter whether the signal is short and loud, long and less loud, consists of several repeated segments or has variable amplitude, as long as the total energy is the same.

The signal energy should be cumulated up to some upper time limit. This limit is debated. In human audiometry it is customary to use 24 hours, in conjunction with the sensible assumption that people are often exposed to loud noise during their workday and then spend the night resting in a quiet place. This assumption is less relevant for marine mammals, but the 24 h maximum was also applied in a precautionary approach by Southall et al. (2007) and retained by National Marine Fisheries Service (2016) and Southall et al. (2019), stressing that it is likely to be very conservative (in the sense that it leads to overprotection). An experiment with harbour porpoises (Kastelein et al., 2016) indicate that the integration time should be at least several hours, however. **For pile driving** it seems reasonable to **use the entire duration of a pile driving event** (i.e. piling of one foundation), which may last several hours, **but not include the time between installations**. This choice is based on the following reasoning:

- During pile driving, the completely dominating source of acoustic energy is from the pile driving itself. Including other sources, such as noise from the pile driving rig and service ships in the estimate of exposure is unlikely to affect the cumulated SEL and therefore unnecessary.

- The turnaround time (time from start of pile driving at one foundation to start on the next foundation) is almost always more than 24 hours and therefore falls in separate assessment periods by the (precautionary) criteria of Southall.

- In the cases where turnaround time is less than 24 hours, the likelihood that the same animal will be exposed twice is very low, as individual animals are expected to be deterred by the pile driving noise.

During actual pile driving operations there may be shorter or longer pauses in hammering, for reasons specific to the particular foundation, such as equipment failure and unforeseen geophysical conditions. As these pauses are undesired and impossible to predict, they should be ignored in the predictive modelling.

Jacket foundations represents a particular case, where a number of smaller pin-piles are installed through jackets on the foundation. The piling time for each pin is typically shorter than piling of a monopile, followed by a pause while the hammer is transferred to the next pin. A precautionary approach to modelling cumulative impact from installation of a jacket foundation is to ignore the pauses between individual pins on the same foundation and simply assume that piling is continuous for a period $n \cdot T$, where n is the number of pins per foundation and T is the time it takes to install a single pin. This way of modelling is equivalent to a scenario where the animals stop moving away from the construction site during the pause between to pin pile installations.

5 Frequency weighting

Animals do not hear equally well at all frequencies. For humans, where an enormous empirical evidence is available in the form of thousands of patients with known noise exposure and measured hearing loss, the consensus is that weighting with a curve roughly resembling the inverted audiogram, the so-called dBA-weighting, provides the best overall prediction of risk of injury (see Houser et al., 2017 for an extensive review). The situation for marine mammals is much less fortuitous, as very few instances of hearing loss have been documented and the noise exposure history of these animals in most cases unknown. See, however, Kastak et al. (2008) and Kastelein et al. (2013a) for notable exceptions.

The first auditory weighting curves, the so-called M-weighting, were proposed by Southall et al. (2007). While conceptually important, the curves themselves are now considered obsolete and have been replaced by weighting functions resembling inversed audiograms (National Marine Fisheries Service, 2016; Southall et al., 2019; Tougaard et al., 2015).

5.1 Marine mammal functional hearing groups

Table 5.1. Comparison of the functional hearing group classification of the three reviews/frameworks. See original references for details and criteria for groupings. The OCW group of Southall et al. (2019) includes the eared seals (Otariids) as well as polar bears and sea otters.

Southall et al (2007)	NMFS/NOAA (2016)	Southall et al. (2019)	DK species
Low frequency cetaceans (LF)	Low frequency cetaceans (LF)	Low Frequency cetaceans (LF)	Minke whale
Mid-frequency cetaceans (MF)	Mid-frequency cetaceans (MF)	High frequency cetaceans (HF)	Pilot whale, whitebeaked dolphin
High frequency cetaceans (HF)	High frequency cetaceans (HF)	Very high frequency cetaceans (VHF)	Harbour porpoise
Pinnipeds (PW)	Phocid seals (PW)	Phocid carnivores (PCW)	Harbour seal, grey seal
	Otariid seals (OW)	Other marine carnivores (OCW)	None
-	-		
-	-	Sirenians (SI)	None

First step in deriving appropriate weighting curves for marine mammals is to obtain information about the hearing abilities of different species, expressed as audiograms. Audiograms are only available for a limited number of species and while some additional species will undoubtedly be added to the list in coming years, a large number of species will remain out of reach for experimental studies for a number of good reasons, such as being very rare and/or difficult to get to in the wild, and so large that they cannot be kept in captivity. For these obvious reasons, but also to simplify matters, it makes sense to divide the species into a limited number of groups, with all members of each group having roughly the same (assumed) hearing capabilities. A sensible criterion for grouping is that the variance between mean audiograms of different species should be smaller than the variance among individuals of the same species (within-group variance larger than between-group variance). A set of marine mammal functional hearing groups was proposed by (Southall et al., 2007). This grouping was largely retained by (National Marine Fisheries Service, 2016), but expanded in (Southall et al., 2019), where also terminology was changed. Table 5.1 above shows the groups, with indication of which groups are relevant in a Danish context. For all practical purposes the differences between the groups is terminology[7]. This report follows the terminology of Southall et al. (2019).

5.2 Composite (group) audiograms

National Marine Fisheries Service (2016) compiled all marine mammal audiogram data available at the time of the review, critically evaluated the studies and created composite audiograms for the different groups. A number of criteria were used in selecting the data used for the composite audiograms (see National Marine Fisheries Service, 2016 for full details), but most important was that they did not include multiple data points at the same test frequency for the same individual (pseudoreplication), but instead included the average of the multiple values. In cases where sufficient data on hearing threshold was available, an idealised audiogram curve with the following equation was fitted to the data:

Equation 5.1

$$T(f) = T_0 + A \log_{10}\left(1 + \frac{F_1}{f}\right) + \left(\frac{f}{F_2}\right)^B$$

This function describes a standardized U-shaped audiogram. Further details on how the parameters were fitted to the data can be found in National Marine Fisheries Service (2016). The resulting audiograms are shown in Figure 5.1 (absolute thresholds) and Figure 5.2 (normalized to lowest threshold of each species) and fitted parameters are listed in Table 5.2.

Table 5.2. Parameters for equation 1 to generate the composite audiograms, both absolute and normalized. From Southall et al. (2019).

	Absolute thresholds					Normalized thresholds				
Species group	**T_0**	**A**	**B**	**F_1**	**F_2**	**T_0**	**A**	**B**	**F_1**	**F_2**
LF/LF	53.19	20	3.2	0.412	9.4	-0.81	20	3.2	0.412	9.4
MF/HF	46.2	35.5	3.56	25.9	47.8	3.61	31.8	4.5	12.7	64.4
HF/VHF	46.4	42.3	17.1	7.57	126	2.48	40.1	17	9.68	126
PW/PCW	43.7	20.1	1.41	10.2	3.97	-39.6	20.5	1.23	368	2.21

[7] The reason for the change in terminology between Southall et al. (2007) and Southall et al. (2019) is anticipation of a need for future subdivision. The mid-frequency cetacean group is thus expected to be resurrected at some point to harbour the beaked whales (Southall, pers. comm.), which have auditory specializations distinct from other odontocetes. Beaked whales are currently included in the High Frequency group.

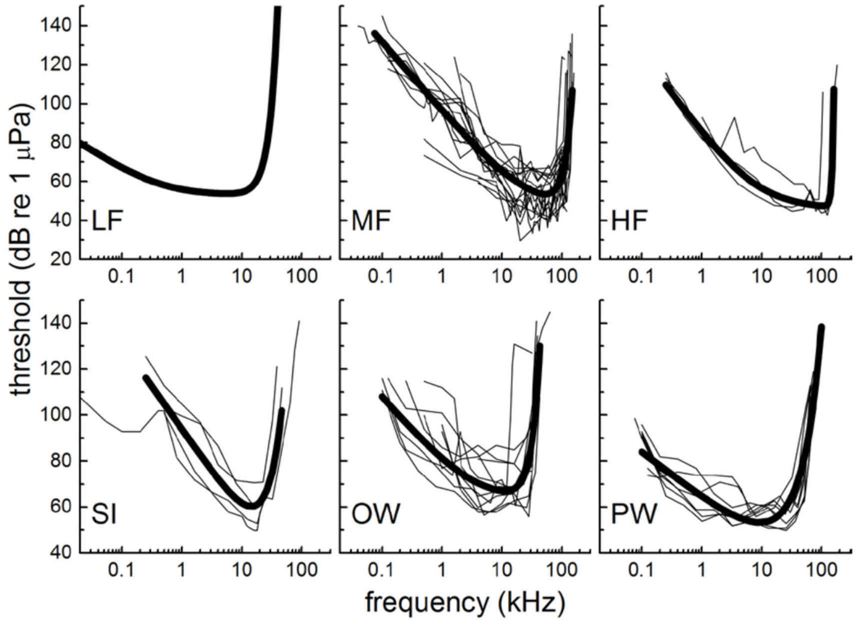


Figure 5.1. Composite audiograms from National Marine Fisheries Service (2016). Thin lines indicate the audiogram data used to fit the composite audiograms. Note that the LF (baleen whale) audiogram is not based on measured data, but inferred otherwise. See for explanation of abbreviations.

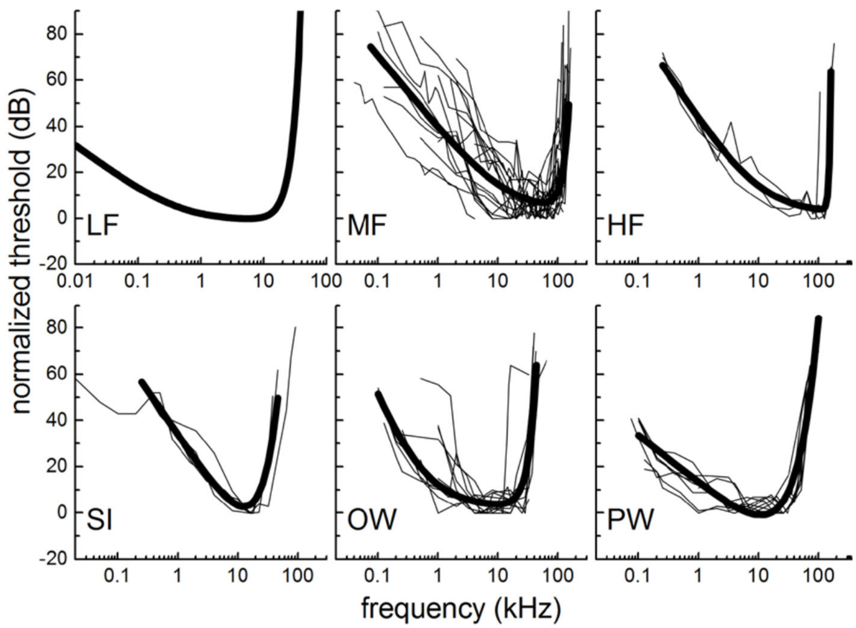


Figure 5.2. Normalized composite audiograms from National Marine Fisheries Service (2016). Thin lines indicate the normalized audiogram data used to fit the composite audiograms. Note that the LF (baleen whale) audiogram is not based on measured data, but inferred otherwise. See Table 5.1 for explanation of abbreviations.

5.3 Weighting functions for TTS thresholds

All experimental data where TTS thresholds had been determined for marine mammals were compiled by (National Marine Fisheries Service, 2016) and used to derive weighting functions. These curves were described by the equation:

Equation 5.2

$$W(f) = C + 10\log_{10}\left(\frac{(f/f_1)^{2a}}{[1+(f/f_1)^2]^a \cdot [1+(f/f_2)^2]^b}\right)$$

Parameters for the individual functional hearing groups are given in Table 5.3. The weighting functions are all inverted U-shaped and thereby resemble an inverse audiogram (see Figure 5.3, left). They are not simply inverted audiograms, however. The slopes a and b of the low-frequency and high-frequency roll off ('legs' of the inverted U) were taken from the composite audiograms, but the cut-off frequencies f1 and f2 and the offset constant C were adjusted to obtain best possible fit to the TTS threshold data. See (National Marine Fisheries Service, 2016) for details.

For display purposes and direct comparison with TTS threshold data it is useful to invert the weighting curve and thereby create an 'exposure-curve', which can be plotted on the same axis as the normalized audiogram and the TTS-thresholds. This exposure curve is given by the following equation:

Equation 5.3

$$E(f) = K - 10\log_{10}\left(\frac{(f/f_1)^{2a}}{[1+(f/f_1)^2]^a \cdot [1+(f/f_2)^2]^b}\right)$$

where all parameters except K are identical to the corresponding weighting curve. The idealized exposure curve is shown in Figure 5.3, right.

C and K are offset parameters, introduced to provide a better fit to TTS-thresholds and allows the weighting curve to deviate more freely from an inverse audiogram. If the weighting curve simply was identical to the inverse audiogram, C would be 0 dB. In that case the parameter K corresponds to the weighted TTS threshold, i.e. the threshold for TTS at the frequency of greatest sensitivity. In the implementation of weighting and exposure functions of National Marine Fisheries Service (2016) the weighting functions are not completely identical to the invert ed au). This means that the weighted TTS threshold equals K + C.

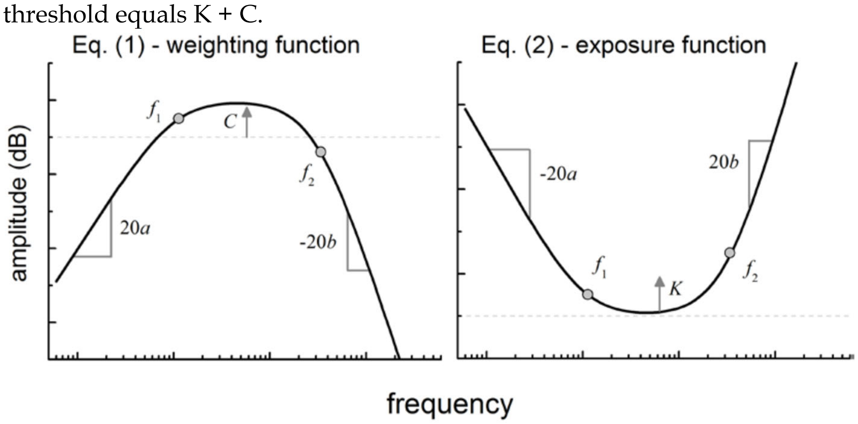


Figure 5.3. Idealized weighting and exposure functions, with indication of the interpretation of the various parameters of the corresponding equations. From National Marine Fisheries Service (2016).

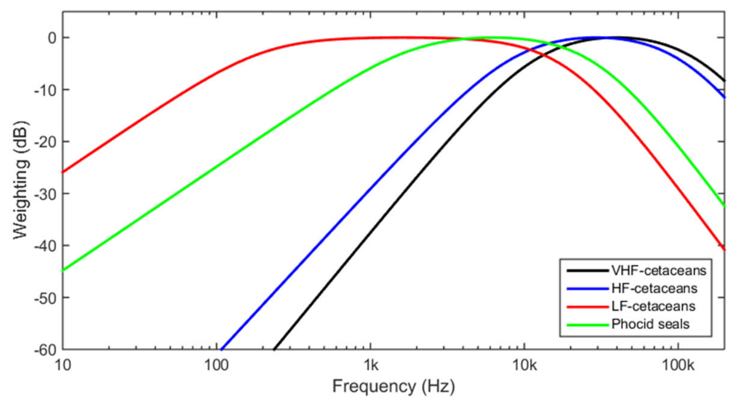
Equation 2 and equation 3 were fitted to empirical data on TTS in the different functional hearing groups, which resulted in the set of parameters shown in Table 5.3. Included is also the TTS threshold for P-type and other sounds, expressed as the weighted sound exposure level (SEL).

Table 5.3. Fitted parameters to generate weighting and exposure functions (equation 2 and equation 3), together with the weighted threshold for TTS for P-type and other sounds. From Southall et al. (2019).

Group	a	b	f1	f2	K	C	Threshold
LF	1	2	0.20 kHz	19 kHz	179 dB	0.13 dB	179 dB SEL
HF	1.6	2	8.8 kHz	110 kHz	177 dB	1.20 dB	178 dB SEL
VHF	1.8	2	12 kHz	140 kHz	152 dB	1.36 dB	153 dB SEL
PCW	1	2	1.9 kHz	30 kHz	180 dB	0.75 dB	181 dB SEL

The corresponding weighting curves are shown in Figure 5.4.

Figure 5.4. Frequency weighting curves proposed by National Marine Fisheries Service (2016) and Southall et al. (2019). Curves for other marine carnivores and sirenians (sea cows) are omitted, as they are not relevant for Danish waters.



The weighting curves are used in assessments of risk of impact. A signal, which contains all or most energy in a narrow frequency band can simply be weighted by adding the corresponding weighting value from the appropriate weighting curve (Figure 5.4) at the relevant frequency. If the noise contains energy in a wider frequency range it is required to pass the signal through a filter with transfer function equal to the appropriate weighting function. This approach can always be used. See Tougaard and Beedholm (2019) for additional information.

6 Species recommendations

In the following, the recommendations from National Marine Fisheries Service (2016) and Southall et al. (2019) are discussed for each of the six selected species considered relevant for Danish waters (Tougaard et al., 2020) and discussed in light of new empirical data obtained after completion of the NMFS/NOAA review, concluding with recommendations for choice of weighting curves and threshold values for noise induced hearing loss.

6.1 Harbour porpoise

6.1.1 P-type sounds

Audiogram for VHF cetaceans is based on three porpoises (Kastelein et al., 2002; Kastelein et al., 2015a; Kastelein et al., 2010) and one south american river dolphin (Inia geoffreyensis, Jacobs and Hall, 1972). Inclusion of the latter is questionable, but makes little difference. The weighting function was derived by National Marine Fisheries Service (2016) and Southall et al. (2019) based on three data points, but a substantial amount of new data has been obtained subsequently. These are plotted in Figure 6.1 and summarized in Table 6.1.

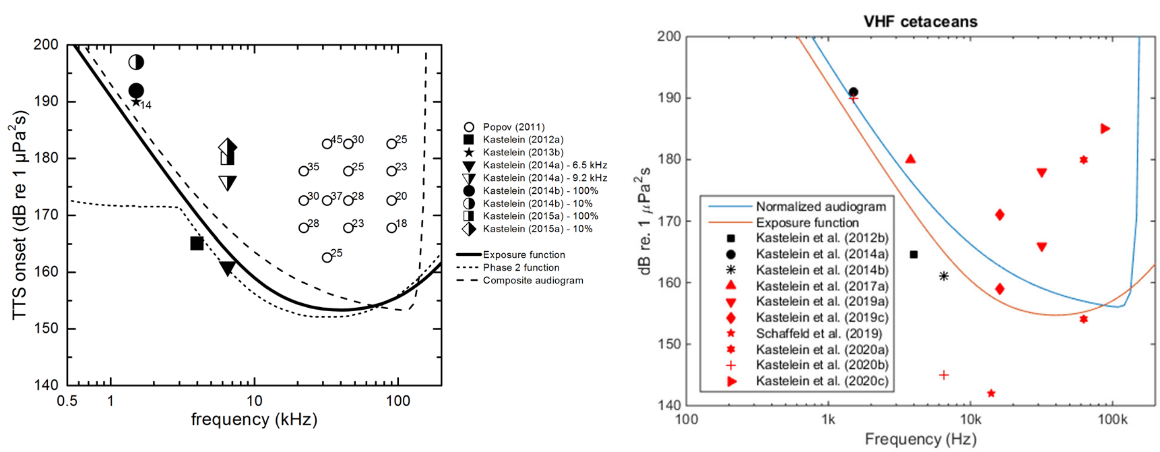


Figure 6.1. TTS threshold data for different experiments with harbour porpoises exposed to P-type and other sounds. Left figure is from National Marine Fisheries Service (2016). Numbers next to data points indicate amount of TTS induced, if more than 6 dB. Right figure contains replot of data points included in the derivation of the weighting function from National Marine Fisheries Service (2016) in black, and new data points in red. Some studies include two animals, indicated by identical symbols. See **Table 6.1** for details.

There is substantial scatter in the data and several of the newer data points are not immediately consistent with the exposure curve by Southall et al. (2019) (red line in Figure 6.1-right). Part of this may be due to variation between individual animals. Animal F05 thus appears less sensitive than predicted by Southall et al. (2019), whereas animal M06 is more in line with the predicted exposure curve). A third animal, F06, appears in line with predictions at 1.5 kHz, whereas it is considerably more sensitive than predicted at 6.5 kHz (Figure 6.1 and Kastelein et al. (2020b)). A fourth animal, in a different facility and different experimental paradigm (Schaffeld et al., 2019) is also considerably more sensitive than predicted. More studies are likely required to settle these issues, but until such data may become available, it is recommended to maintain the weighting function of Southall et al. (2019) and the derived thresholds for TTS and PTS for P-type sounds and other sounds (Table 6.2).

Table 6.1. Studies of temporary threshold shift in harbour porpoises and other closely related species.

Reference	Fatiguing sound	Threshold	Comments	NMFS
I-type sounds				
Lucke et al. (2009)	Airgun	154 dB SEL[8]	Single airgun pulse	Yes
Kastelein et al. (2015a)	Pile driving playback	180 dB SEL	1 hour exposure	Yes
Kastelein et al. (2016)	Pile driving playback	175 dB SEL	0.25-6 hours exposure, same animal as 2015a	No
Kastelein et al. (2017b)	Airgun	191 dB SEL	20 airgun shots	No
Kastelein et al. (2020e)	Airgun	>199 dB SEL	Same animal as 2017b	No
Other sounds				
Popov et al. (2011)	20-100 kHz	na	Finless porpoise. 18-45 dB of TTS	(Yes)[9]
Kastelein et al. (2012b)	4 kHz octave band	164.5 dB SEL		Yes
Kastelein et al. (2014a)	1-2 kHz sweep	191 dB SEL	100% duty cycle	Yes
Kastelein et al. (2014b)	6.5 kHz pure tone	161 dB SEL	6.5 kHz test frequency	Yes
Kastelein et al. (2015b)	6.5 kHz pure tone	180 dB SEL	Same animal as Kastelein et al. (2014)	No
Kastelein et al. (2017a)	3.5-4.1 kHz FM	178 dB SEL	53C sonar signal	No
Kastelein et al. (2019a)	32 kHz 1/6-octave band	166 dB SEL	Animal M06	No
	32 kHz 1/6-octave band	178 dB SEL	Animal F05	No
Kastelein et al. (2019d)	16 kHz 1/6-octave band	159 dB SEL	Animal M06	No
	16 kHz 1/6-octave band	171 dB SEL	Animal F05	No
Schaffeld et al. (2019)	14 kHz pure tone	142 dB SEL	Seal scarer signal	No
Kastelein et al. (2020a)	63 kHz 1/6-octave band	154 dB SEL	Animal M06	No
	63 kHz 1/6-octave band	180 dB SEL	Animal F05	No
Kastelein et al. (2020b)	1.5 kHz 1/6-octave band	190 dB SEL	Animal F06	No
	6.5 kHz pure tone	145 dB SEL	Animal F06	No
Kastelein et al. (2020c)	88 kHz 1/6-octave band	185 dB SEL	Animal F05	No

6.1.2 I-type sounds

Much fewer studies are available with I-type sounds. A seminal study is Lucke et al. (2009), which showed that TTS could be induced in a harbour porpoise by exposure to a single pulse from an airgun at a received unweighted (broadband) sound exposure level of 154 dB re. 1 µPa²s. This threshold has been the foundation of legislation regarding pile driving in for example Germany (German Federal Ministry for the Environment and Nuclear Safety, 2013) and has thus been instrumental in driving the development of effective sound attenuation devices. The signal used by Lucke et al. (2009) was broadband and the frequency spectrum not well characterized, however. This means that the threshold is difficult to generalize, as it cannot be adjusted appropriately with the VHF frequency weighting curve. Two other studies are available, with better characterized stimuli. Kastelein et al. (2015a) thus measured TTS in a porpoise after exposure to a 1 hour sequence of pile driving pulses and reported a threshold of 180 dB re. 1 µPa²s, unweighted, cumulated over all pulses (SELcum). A subsequent study with same animal and same fatiguing sounds, but with variable exposure duration (Kastelein et al., 2016), reported a slightly lower threshold for TTS: 175 dB re. 1 µPa²s, unweighted. Two additional studies (Kastelein et al., 2020e; Kastelein et al., 2017b) with

[8] There is some variation in this threshold, depending on authors and values between 152 and 155 can be found in different sources. The variation is due to different definitions of TTS-threshold, ranging from lowest level where a threshold elevation, no matter how small, can be reliably detected, to a more conservative definition of the exposure required to elevate the threshold 6 dB above average baseline level. These differences are without practical significance.

[9] Not included in fitting of weighting function, but included in review.

airgun pulses as fatiguing sounds reported unweighted TTS thresholds for the same animal of 191 and 199 dB re. 1 µPa²s, respectively.

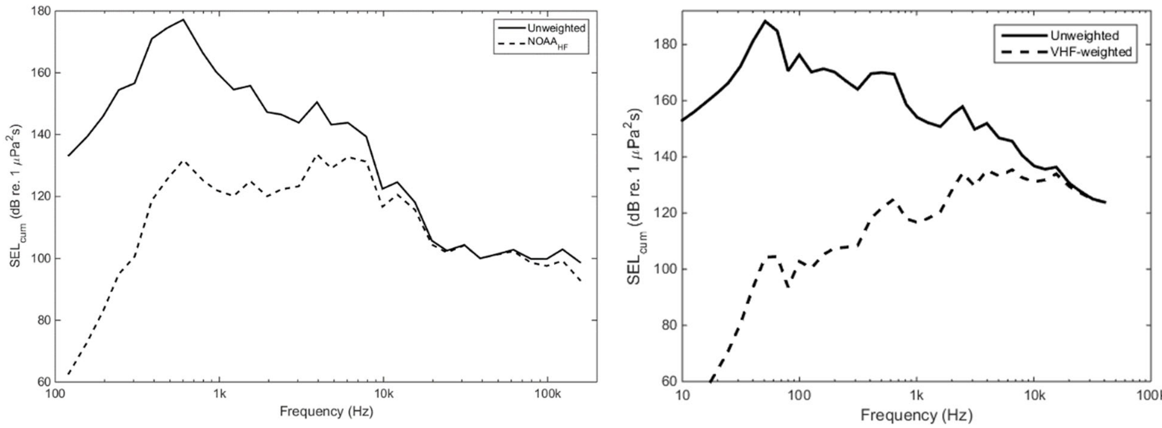


Figure 6.2. Third-octave spectrum of pile driving stimulus used by Kastelein et al. (2015a) (left) and airgun stimulus used by Kastelein et al. (2017b) (right). Solid lines indicate unweighted spectra adjusted to a total SELcum equal to the TTS threshold of the experiments (180 dB re. 1 µPa²s for pile driving, 191 dB re. 1 µPa²s for airgun) and broken lines the same spectra weighted with the VHF-cetacean weighting function. Left figure modified from Tougaard and Dähne (2017), right figure original.

As the frequency spectra of the signals are known, it is possible to weigh them with the VHF-weighting curve and thereby estimate the weighted threshold for TTS. This was done for the first study (Kastelein et al., 2015a) by Southall et al. (2019) and Tougaard and Dähne (2017) and provided a weighted threshold for TTS of 140 dB re. 1µPa²s (see Figure 6.2 left). The same can be done for the threshold from Kastelein et al. (2016), Kastelein et al. (2017b) (Figure 6.2, right) and Kastelein et al. (2020e). All thresholds are listed in Table 6.1.

Table 6.1. Thresholds for inducing TTS by I-type sounds.

Reference	Sound	TTS threshold (VHF-weighted)	Used in Southall et al (2019)
Kastelein et al. (2015a)	Pile driving	140 dB re. 1 µPa²s	Yes
Kastelein et al. (2016)	Pile driving	135 dB re. 1 µPa²s	No
Kastelein et al. (2017b)	Airgun	144 dB re. 1 µPa²s	No
Kastelein et al. (2020e)	Airgun	152 dB re. 1 µPa²s	No

There is considerable scatter in the thresholds. Kastelein et al. (2020c) argue that the high threshold obtained in that study may be due to 'self-mitigation' by the experimental animal, more precisely an ability of the experimental animal to voluntarily reduce the hearing sensitivity of the ear by contraction of the stapedial muscle in the middle ear. Such ability is well-known from humans and has been demonstrated also in odontocetes (Nachtigall and Supin, 2014; Nachtigall et al., 2016). This leaves three threshold estimates between 135 and 144 dB re. 1 µPa²s, which does not seem to indicate a need to revise the threshold proposed by Southall et al. (2019), based on the results from Kastelein et al. (2015a). The recommended thresholds for TTS and PTS are therefore given in Table 6.2.

Table 6.2. Proposed thresholds for inducing TTS and PTS in porpoises. From Southall et al. (2019)

	TTS	PTS
P-type and other sounds	153 dB SEL VHF weighted	183 dB SEL VHF weighted
I-type sounds	140 dB SEL VHF weighted	155 dB SEL VHF weighted

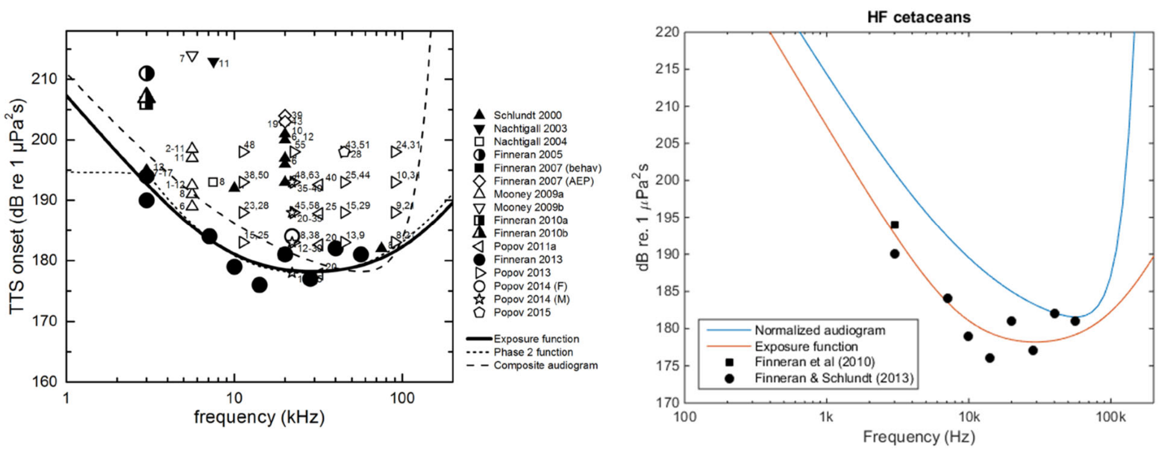


Figure 6.3. Empirical TTS measurements for HF cetaceans for P-type sounds. Left figure is from National Marine Fisheries Service (2016). Numbers next to data points indicate amount of TTS induced, if more than 6 dB. Right figure contains replot of data points included in the derivation of the weighting function from National Marine Fisheries Service (2016).

6.2 White-beaked dolphin

White-beaked dolphin is grouped in the HF-cetacean group by Southall et al. (2019). This group is the default group for odontocetes, as it contains all odontocetes not specifically considered to belong in the VHF-group. The weighting function and TTS/PTS thresholds are based exclusively on data from bottlenose dolphins (*Tursiops truncatus*) and beluga (*Delphinapterus leucas*). The empirical data considered by National Marine Fisheries Service (2016) and the fitted composite audiogram and exposure function are shown in **Error! Reference source not found.**. As no new data have become available since 2016 the recommendations of National Marine Fisheries Service (2016) and Southall et al. (2019) are considered best available (**Table 6.3**).

Table 6.3. Proposed thresholds for inducing TTS and PTS in dolphins. From Southall et al. (2019)

	TTS	PTS
P-type sounds	178 dB SEL HF weighted	185 dB SEL HF weighted
I-type sounds	170 dB SEL HF weighted	198 dB SEL HF weighted

6.3 Minke whale

The LF cetacean group contains all of the mysticetes (baleen whales), including minke whale. Although there have been no direct measurements of hearing sensitivity in any mysticete, an audible frequency range of approximately 10 Hz to 30 kHz was estimated by Southall et al. (2019) from observed vocalization frequencies, observed reactions to playback of sounds, and anatomical analyses of the auditory system, as well as finite element modelling (Cranford and Krysl, 2015). In the same way there is a total absence of data on TTS in mysticetes. Thresholds are therefore extrapolated from data from bottlenose dolphins and beluga whales (**Tabel 6.4**).

Tabel 6.4. Proposed thresholds for minke whale. From Southall et al. (2019).

	TTS	PTS
P-type sounds	179 dB SEL LF weighted	199 dB SEL LF weighted
I-type sounds	168 dB SEL LF weighted	183 dB SEL LF weighted

6.4 Long-finned pilot whale and other deep-diving odontocetes

No auditory data is available from long-finned pilot whale and only very limited data on the audiogram of a beaked whale exists (Pacini et al., 2011), not sufficient to construct a composite audiogram. Although there is good reason to expect hearing of beaked whales to deviate from the other HF cetaceans (based on Pacini et al., 2011 and hhe fact that the sounds they make deviate considerably from delphinid odontocetes), there is at present not any data available to base a separate recommendation on. The best choice is therefore the HF-thresholds derived from delphinid data (Table 6.5).

Table 6.5. Thresholds for TTS and PTS for long-finned pilot whales and other deep-diving odontocetes. From Southall et al. (2019).

	TTS	PTS
P-type sounds	178 dB SEL HF weighted	185 dB SEL HF weighted
I-type sounds	170 dB SEL HF weighted	198 dB SEL HF weighted

6.5 Harbour seal

A composite audiogram for phocid seals was constructed by Southall et al. (2019) on the basis of measurements from primarily harbour seals, but also elephant seal, largha seal and spotted seal.

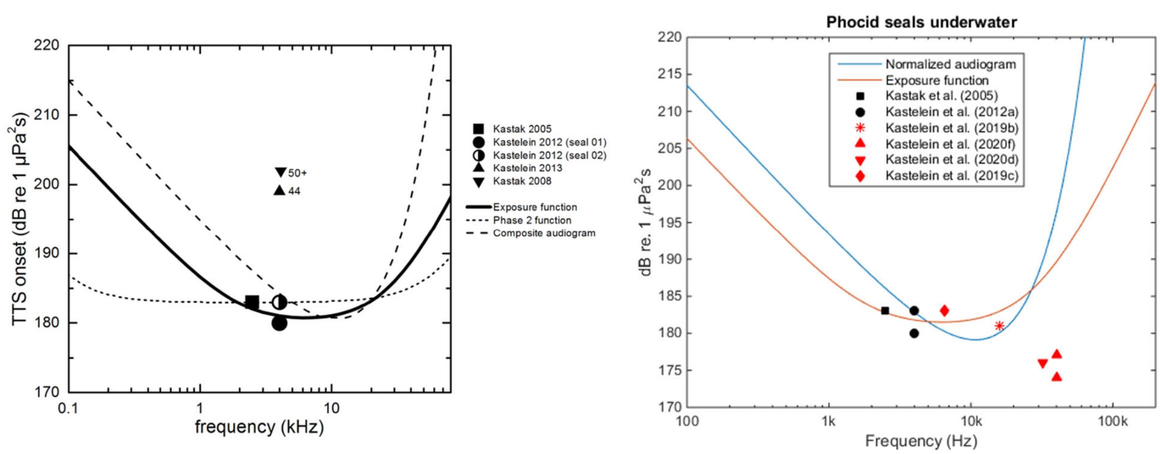


Figure 6.4. Exposure function, audiogram and TTS thresholds for phocid seals. Left figure is from National Marine Fisheries Service (2016). Numbers next to data points indicate amount of TTS induced, if more than 6 dB. Right figure contains replot of data points included in the derivation of the weighting function from National Marine Fisheries Service (2016) in black, and new data points in red. See **Table 6.** for details.

A few studies were available to Southall et al. (2019), with additional data available after the review (See Table 6.7 for a complete list). All thresholds for P-type sounds are shown in Figure 6.3.

Two of the more recently obtained thresholds at 6.5 kHz and 16 kHz align well with predictions of the exposure curve from Southall et al. (2016), whereas three thresholds (one at 32 kHz and two at 40 kHz) are significantly lower than predicted, which may indicate a need to revisit the shape of the weighting curve at higher frequencies. For lower frequencies, relevant to pile driving noise, the new data does not provide reason to change the recommended threshold for TTS from Southall et al. (2019).

Contrary to the other functional hearing groups the PTS threshold was not extrapolated, as two relevant studies were available. PTS was induced due to an experimental error by Kastak et al. (2008), where a harbour seal was exposed to a 60 s tone at 4.1 kHz at a total SEL of 202 dB re. 1 μPa^2s. A second experiment (in a different facility and on a different animal) produced a very strong TTS (44 dB), also by accident, by exposure to 60 minutes of 4 kHz octave band noise at a SEL of 199 dB re. 1 μPa^2s (Kastelein et al., 2013a). The level of TTS is considered to have been very close to inducing PTS. PTS thresholds could therefore be taken directly from these data points.

Table 6.7. Studies of temporary threshold shift in harbour seals and other phocid seals. All thresholds are unweighted.

Reference	Fatiguing sound	TTS threshold	Comments	NMFS
I-type sounds				
Reichmuth et al. (2016)	Airgun	> 181 dB SEL	Ringed seal and spotted seal	No
Kastelein et al. (2018)	Pile driving	193 dB SEL		No
P-type and other sounds				
Kastak et al. (2005)	2.5 kHz octave band	183 dB SEL		Yes
Kastak et al. (2008)	4.1 kHz pure tone	PTS at 202 dB SEL	7-10 dB PTS	Yes
Kastelein et al. (2012a)	4 kHz octave-band	180 + 183 dB SEL	2 animals	Yes
Kastelein et al. (2013a)	4 kHz octave-band	near PTS at 199 dB SEL	44 dB TTS	Yes
Kastelein et al. (2019c)	6.5 kHz	183 dB SEL		No
Kastelein et al. (2019b)	16 kHz 1/6 octave	181 dB SEL	Another seal no TTS	No
Kastelein et al. (2020d)	32 kHz 1/6 octave	176 dB SEL		No
Kastelein et al. (2020f)	40 kHz 1/6 octave	174 dB SEL		No
	40 kHz 1/6 octave	177 dB SEL		No

Two experiments have been published involving I-type sounds as fatiguing sounds. One set of experiments on a ringed seal (*Pusa hispida*) and a spotted seal (*Phoca largha*) exposed them to air gun pulses at SEL up to a maximum of 181 dB re. 1 μPa^2s (unweighted), but did not induce TTS in any of the seals (Reichmuth et al., 2016). A second study (Kastelein et al., 2018) used pile driving noise as fatiguing noise and measured an unweighted TTS threshold of 193 dB re. 1μPa^2s. Frequency spectra are available for both sounds and appropriate frequency weighting (PCW) can be performed (Figure 6.5). In Reichmuth et al. (2016) the loudest sound (which did not produce TTS) was thus 162 dB re. 1 μPa^2s PCW weighted, whereas the TTS threshold from Kastelein et al. (2018) equals 183 μPa^2s PCW weighted.

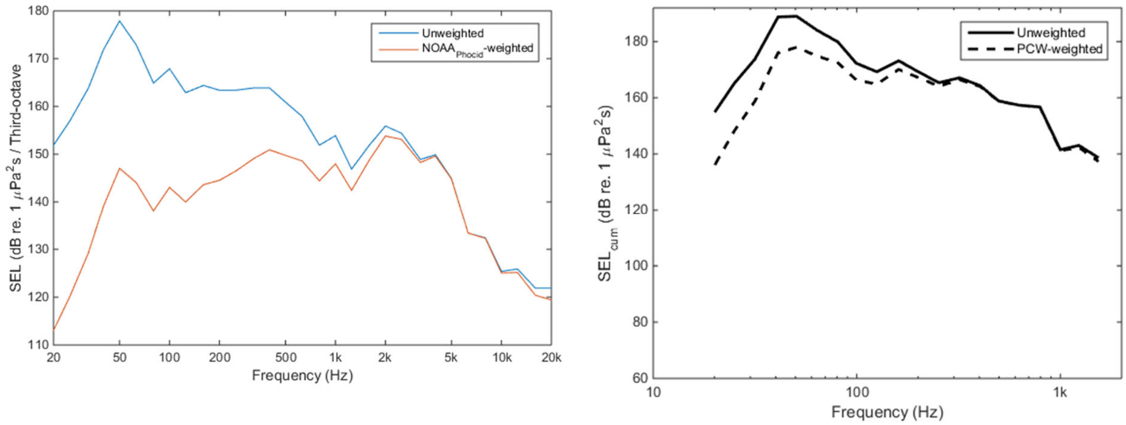


Figure 6.5. Left: Third-octave spectrum of the loudest airgun pulse used by Reichmuth et al. (2016), both as unweighted (blue) and $NOAA_{phocid}$-weighted (red). Right: Pile driving sound used by Kastelein et al. (2018), both unweighted and PCW-weighted.

These numbers should be compared to the TTS threshold for I-type sounds of Southall et al. (2019) of 170 dB re. 1 µPa²s. This threshold was inferred indirectly from the P-type sounds and relationship between P-type and I-type thresholds observed in odontocetes. The TTS threshold of Southall et al. (2019), when compared to the result of Kastelein et al. (2018), may therefore be set too low. However, based on a precautionary approach, it is proposed to retrain the suggested threshold of Southall et al. (2019). These thresholds for harbour seals are thus given in Table 6.8.

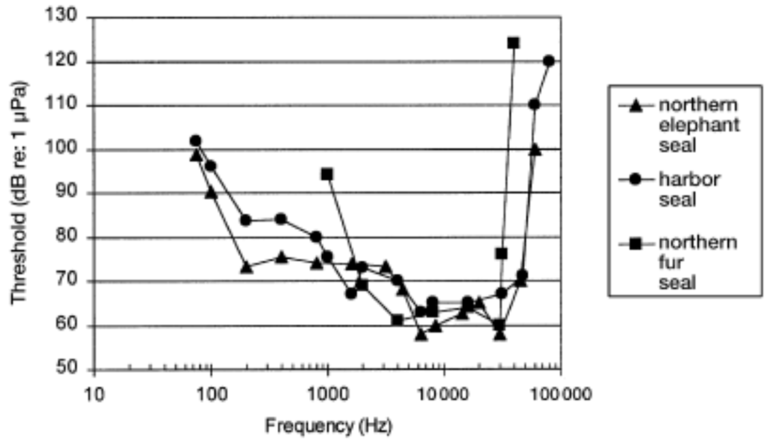
Table 6.8. Proposed thresholds for TTS and PTS for harbour seal.

	TTS	PTS
P-type sounds	181 dB SEL PCW weighted	201 dB SEL PCW weighted
I-type sounds	170 dB SEL PCW weighted	185 dB SEL PCW weighted

6.6 Grey seal

No information is available about hearing in grey seals or their susceptibility to noise induced hearing loss. Adult grey seals are larger than harbour seals (2-3 times by weight) and some scaling of the frequency range of best hearing could therefore be expected. A single audiogram is available for a female northern elephant seal (*Mirounga angustirostris*) (Kastak and Schusterman, 1999), another phocid seal, considerably larger than harbour seals. Superficial comparison of the audiogram with that of a harbour seal measured in the same facility does not indicate substantial differences between the audiograms of the two species. This supports that the harbour seal audiogram (and hence also weighting function) is a useful proxy for grey seals as well, pending empirical data from this species.

Figure 6.6. Audiograms of three different seals. Two true seals: northern elephant seal and harbour seal and one earled seal: northern fur seal. From Kastak and Schusterman (1999).



No TTS thresholds or any other information on TTS in grey seals is available. The thresholds proposed for harbour seals are therefore the best available.

Table 6.9. Proposed thresholds for TTS and PTS for grey seal

	TTS	PTS
P-type sounds	181 dB SEL PCW weighted	201 dB SEL PCW weighted
I-type sounds	170 dB SEL PCW weighted	185 dB SEL PCW weighted

7 References

Cranford, T.W., and P. Krysl. 2015. Fin Whale Sound Reception Mechanisms: Skull Vibration Enables Low-Frequency Hearing. *PlosOne*. 10:1-17.

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