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Underwater noise and marine mammals

Review of best available knowledge in relation to construction of offshore wind farms in the Swedish Baltic

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Preface

This scientific briefing was commissioned by Rambøll Sweden to serve as background material in relation to impact assessments of offshore wind farm projects in Swedish waters. The content parallels advise given to the Danish Energy Agency as background for their revision of guidelines regarding assessment of impact from pile driving noise (Tougaard, 2021b; a).

The content of this briefing was scoped in cooperation with Rambøll, but the content and conclusions are the sole responsibility of the author. The main purpose of the briefing is to provide a contemporary review of the experimental evidence behind criteria and thresholds usable for assessing risk of injury and behavioural disturbance of marine mammals by loud impulsive noise.

1 Marine mammals in the Southern Baltic

Three species of marine mammals are regularly present in the waters south of Skåne and Blekinge: Harbour porpoise (tumlare, *Phocoena phocoena*), harbour seal (knubbsäl, *Phoca vitulina*) and grey seal (gråsäl, *Halichoerus grypus*). In addition to these three, a number of other species, especially whales and dolphins, occur as rare visitors. These rare visitors occur so infrequently that they are considered irrelevant for impact assessments and are not treated further (Tougaard *et al.*, 2020).

1.1 Harbour porpoise

Harbour porpoises are abundant in the North Sea and Danish Straits, with a pronounced decline in density in the waters west of Bornholm. Morphological differences, genetic evidence and tracking of movements of individuals support separation of porpoises in the area into three different populations: a North Sea population[1], a Danish Straits population and a Baltic proper population (Galatius *et al.*, 2012; Sveegaard *et al.*, 2015). The borders between the populations are not strict and change with time of year, but are located in central Kattegat and in the waters south of Skåne (Figure 1.1).

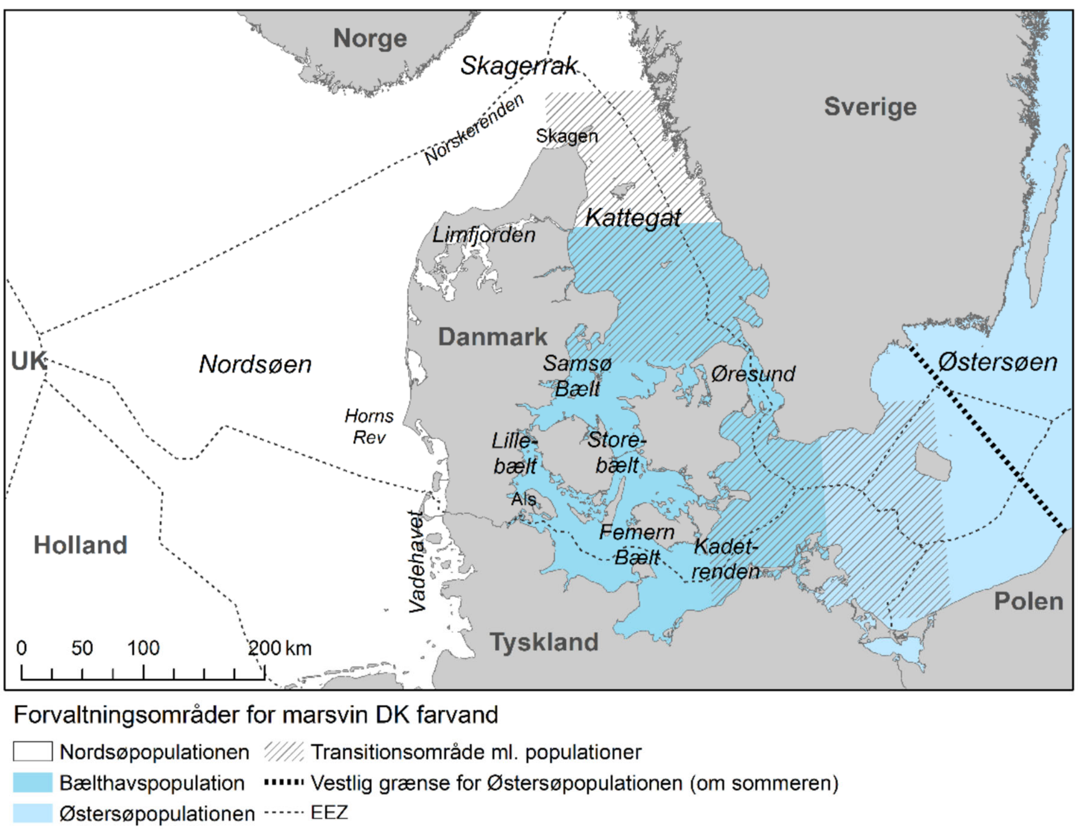

Figure 1.1. Management areas for populations of porpoises in the Danish Straits. Three populations inhabit these waters: a North Sea population (Nordsøpopulationen), which reaches into Kattegat, a Kattegat/Danish Straits population (Bælthavspopulationen), which reaches into the waters around Bornholm, and a Baltic proper population (Østersøpopulationen) which is believed to reach out to the Sound (Drogden) and the Kadet Trench. From Sveegaard *et al.* (2018).

[1] There may be further subdivision within the North Sea, but no empirical evidence is available on this topic.

Whereas the North Sea and Danish Straits populations are considered to be in favourable conservation status (Fredshavn *et al.*, 2019; SLU Artdatabanken, 2020), the Baltic proper population is very small and assessed as critically endangered (SLU Artdatabanken, 2020). There are no reliable abundance estimates for the Baltic population, but current best estimate is 490 individuals (95% confidence interval 66-1,143), based on the SAMBAH project, which used passive acoustic monitoring (Amundin *et al.*, 2021).

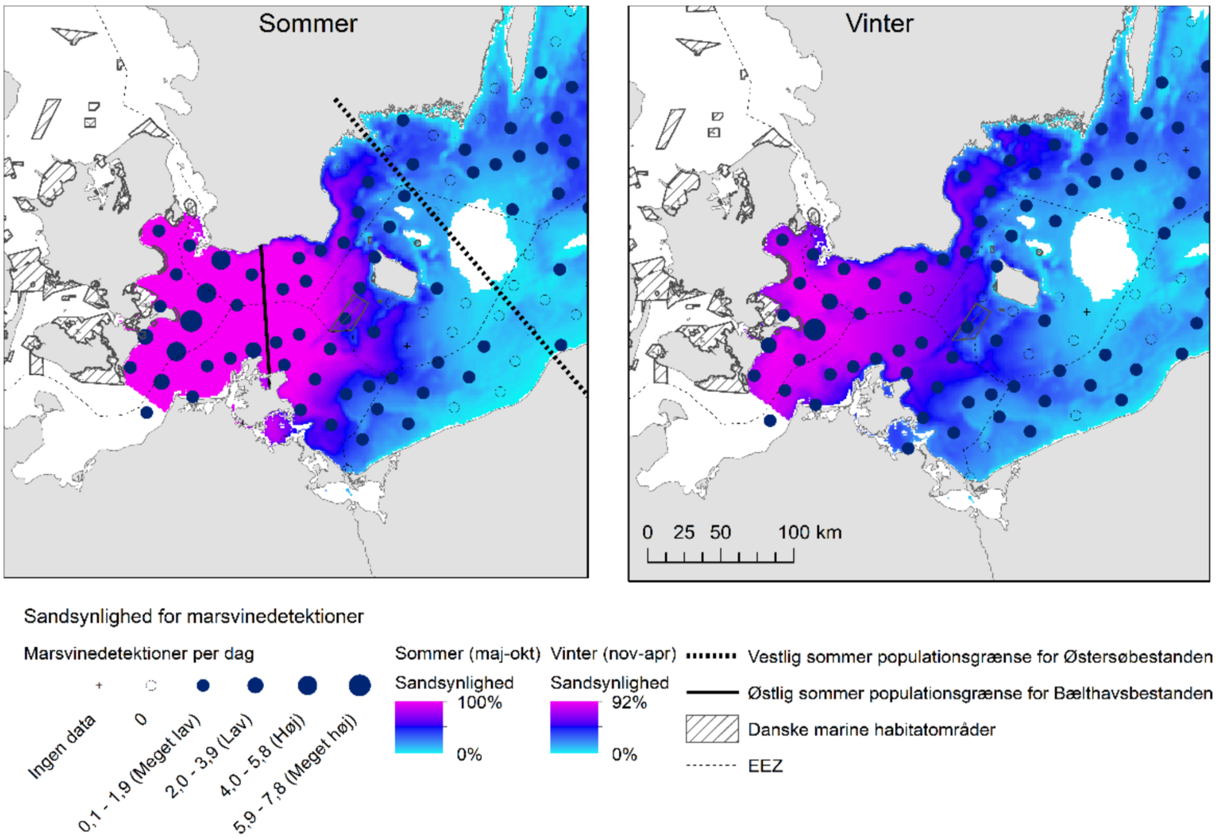

Figure 1.2. Probability of acoustic detections of porpoises (on a daily basis) at passive acoustic monitoring stations deployed as part of the SAMBAH project (blue circles). Likelihood of encountering porpoises (of any population) was spatially modelled and is indicated by coloration (purple being highest likelihood). During summer months the area between the two black lines are considered of lesser importance to both populations. From Sveegaard *et al.* (2018)

It is not possible to assign individuals to populations from visual or acoustic observations, which means that information about borders between the two populations and possible migration and exchange between the populations has to be inferred from indirect evidence. This evidence (Verfuss *et al.*, 2007; Sveegaard *et al.*, 2015; Carlén *et al.*, 2018; Amundin *et al.*, 2021) points to an annual displacement east-west in the distribution. Animals in the waters south of Skåne are thus believed to be predominantly from the Danish Straits population in summer months, whereas some animals from the Baltic proper population migrate into these waters during winter (figure 1.2). As stated, the evidence for these migrations is indirect and weak and it is therefore not possible to conclude how likely it is that a particular harbour porpoise observed in the waters south of Skåne belongs to the critically endangered Baltic proper population versus the Danish Straits population in good conservation status. Available data, most importantly from the SAMBAH study, points in the direction that the likelihood of encountering porpoises from the Baltic proper in the waters south of Skåne is higher in winter than in summer.

1.2 Harbour seals

Harbour seals are abundant in the western Baltic, with a number of significant breeding and haul-out locations along the coast. Of relevance to the waters south of Skåne are Falsterbo, Saltholm and Rødsand, of which Falsterbo is the easternmost. There is a separate population of harbour seals further into the Baltic, in Kalmarsund, but this population is considered to be isolated and not present in waters west of Bornholm (Bergström, 2014). Movement of harbour seals tagged on Falsterbo are shown in figure 1.3. The harbour seals in the western Baltic are assessed to be in favourable conservation status (Fredshavn *et al.*, 2019; SLU Artdatabanken, 2020).

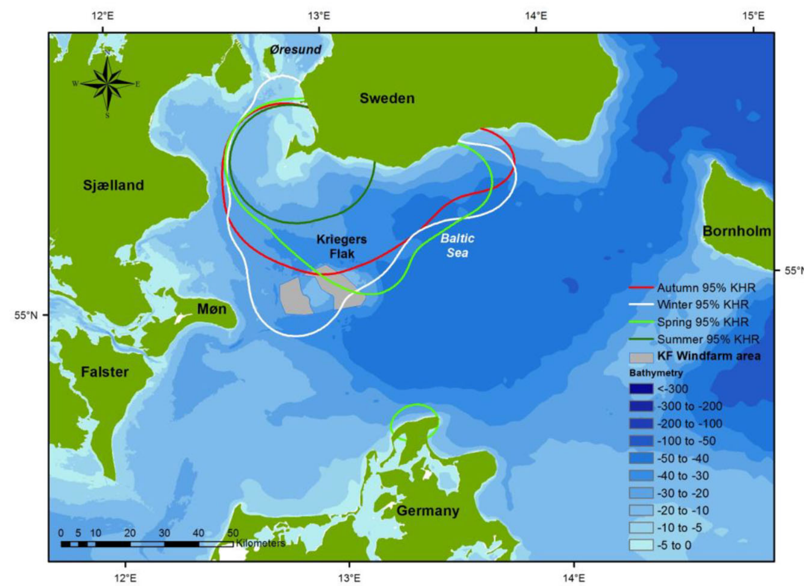

Figure 1.3. Distribution (Kernel home ranges) for harbour seals tagged on Falsterbo and separated into season of the year. Each curve shows the 95% kernel. From Dietz *et al.* (2015).

1.3 Grey seals

Grey seals are abundant in the Baltic proper and the population is expanding westward (Galatius *et al.*, 2020). All animals in the Baltic are considered to belong to the same population, assessed to be in favourable conservation status (Fredshavn *et al.*, 2019; SLU Artdatabanken, 2020) and satellite tracked individuals move throughout the distribution range from the western Baltic (Fasterbo and Rødsand) to the inner Baltic (Estonia). Movement of grey seals tagged on Falsterbo are shown in figure 1.4.

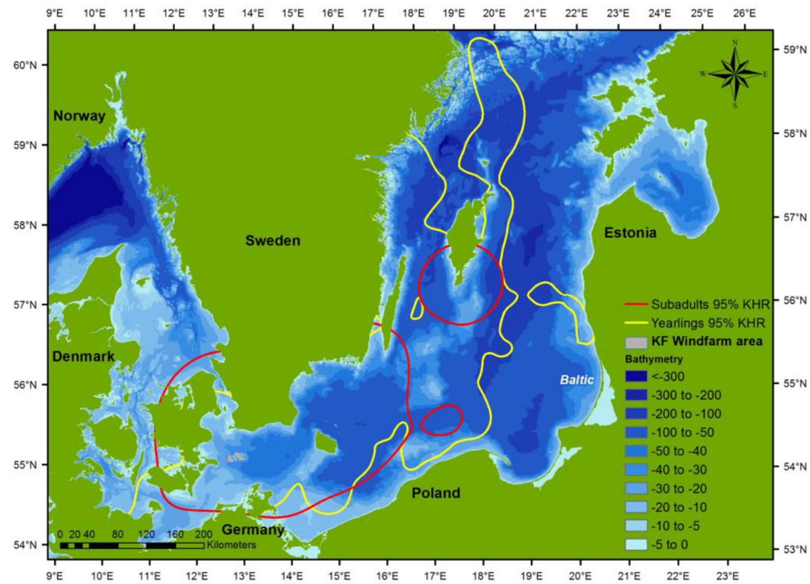

Figure 1.4. Distribution (Kernel home ranges) for grey seals tagged on Falsterbo and separated into subadults and yearlings. Each curve shows the 95% kernel. From Dietz *et al.* (2015).

2 Terminology and key acoustical concepts

Some useful definitions are provided below. Further details can be found in Southall *et al.* (2019) and Tougaard (2021b). Sound is pressure fluctuations around the ambient pressure and can be quantified in different ways. In relation to impact, one often wants to quantify how loud a sound is. This can be done in different ways depending on the type of sound and the context, as a result some metrics of quantification are more appropriate than others.

2.1 Behavioural disturbance: sound pressure level

When dealing with behavioural reactions to noise the most appropriate measure is one that quantifies the loudness of the sound, which is the perceived intensity of the sound. The perceived loudness of a sound depends on the frequency of the sound. For example, a sound which is outside the frequency range of best hearing of the animal will have a lower perceived loudness than a sound in the frequency range of best hearing. Loudness also depends on the duration of the sound. Up to a certain duration, often termed the integration time of the auditory system, the loudness of a sound will increase with increasing duration, whereas it remains independent of duration when longer than the integration time. The integration time of most mammalian ears studied to date are in the range of some hundred milliseconds. A first approximation to the loudness of a sound is therefore the maximum of a running mean of the sound intensity, weighted according to the frequency dependent sensitivity of the ear (audiogram, see section 3.1). See Tougaard *et al.* (2015); Tougaard and Beedholm (2019) for further details. Briefly, the running mean should be performed over an integration time similar to the integration time of the animal's auditory system, customarily assumed to be 125 ms for mammals in general and also applicable to marine mammals (Tougaard *et al.*, 2015). Furthermore, the auditory frequency weighting should be done with a suitable weighting function. For marine mammals such functions have been provided by Southall *et al.* (2019) and of particular relevance to the Baltic Sea are the very high-frequency (VHF) weighting curve applicable to harbour porpoises and the phocid seal weighting curve (PCW) applicable to harbour seals, grey seals and ringed seals.

2.2 Injury to hearing: sound exposure level

When assessing risk of noise-inflicted hearing loss, the most appropriate measure has turned out to be the sound exposure level, which is a measure of the total acoustic energy in the sound, weighted according to frequency dependent sensitivity as for the sound pressure levels above (Finneran, 2015; Southall *et al.*, 2019). The cumulated sound exposure level (SEL) should be calculated over the duration of the exposure, up to some upper limit. This upper limit is subject to discussion, but is at least several hours and tentatively assumed to be no more than 24 hours (Southall *et al.*, 2007; Southall *et al.*, 2019). If the sound exposure under assessment therefore has a duration of less than 24 hours, such as is the case for a typical pile driving event, the cumulated SEL should be calculated over the entire duration of the pile driving event (Tougaard, 2021b).

Note that the units of sound pressure level (dB re. 1 µPa) and sound exposure level (dB re. 1 $\mu Pa^2 s$) are different, as they express two entirely different physical properties (pressure vs. energy). This means that two separate thresholds are needed in impact assessments: one expressed in units of pressure relevant for disturbance and one in the unit of energy, relevant for injury to hearing.

3 Hearing and sensitivity to underwater noise

Marine mammals have acute underwater hearing and they depend on this hearing for orientation, communication and prey capture. This, in turn, means that underwater noise generated by human activities have the potential to negatively affect marine mammals.

3.1 Audibility

The fundamental characterisation of hearing sensitivity of animals is through the audiogram, expressing the lowest audible sound levels as function of frequency. Audiograms of harbour porpoises and harbour seals are shown in figure 3.1. It is clear from the audiograms that harbour porpoises have significantly better hearing than harbour seals at high frequencies (above approximately 7 kHz), whereas the opposite is true for lower frequencies (Kastelein *et al.*, 2009; Kastelein *et al.*, 2010).

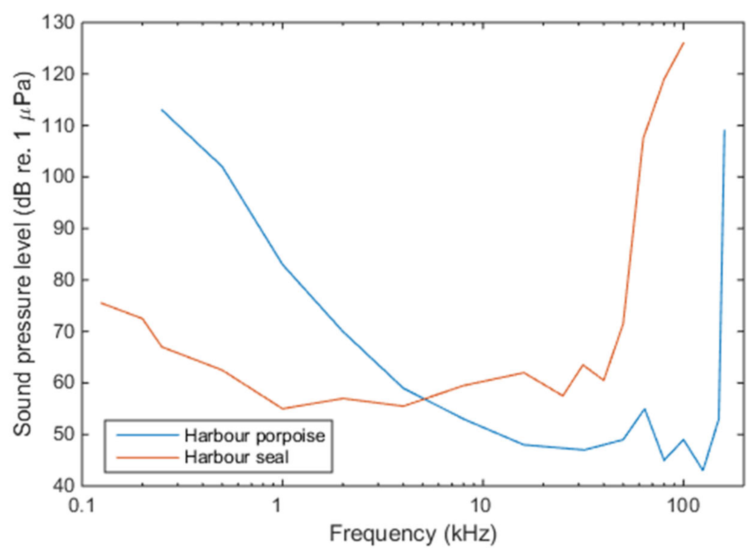

Figure 3.1. Audiograms of harbour porpoises (Kastelein *et al.*, 2010) and harbour seals (Kastelein *et al.*, 2009). No audiogram is available for grey seals, so in the absence of empirical data it is assumed that the hearing of grey seals is roughly similar to harbour seals (Southall et al., 2019).

3.2 Types of impact of noise

Underwater noise can impact marine mammals in different ways. Very loud noise can inflict acute and direct damage (injury), whereas a range of other effects can be induced by sound of lower intensity. These other effects can include direct behavioural reactions to the noise, secondary effects through interference with perception of other sounds (masking), and long-term effects on the physiology (elevated stress hormone levels, cardiovascular responses etc.).

3.2.1 Injury

Very loud noise, which in reality may be limited to the shock wave from underwater explosions, can cause direct damage to biological tissue (acoustic trauma), which can be fatal (Yelverton *et al.*, 1973; Hill, 1978; Young, 1991; Ketten, 1995; Lewis, 1996; Lance and Bass, 2015; Lance *et al.*, 2015). Some authors have provided tentative thresholds for safe exposures, such as Lance *et al.* (2015), but it is beyond the scope of this briefing to enter a detailed discussion of this. Certain types of sound, in particular military sonars, have been conclusively linked to strandings and deaths of marine mammals, in particular cetaceans (Fernández *et al.*, 2005). These lethal effects are believed not to be induced by the sound itself, however. Instead, the loud sounds are believed to induce behavioural reactions (antipredator behaviours) in the whales, which lead to secondary and often fatal physiological problems, such as nitrogen gas embolism. The physiological injuries and possible death of animals exposed to military sonar should therefore be considered not as a direct injury, but a secondary injury caused by the primary behavioural reaction to the noise.

3.2.2 Temporary and permanent threshold shift

Since the comprehensive review by Southall *et al.* (2007) there has been general agreement on temporary and permanent hearing threshold shifts as precautionary criteria for injury due to noise exposure. This approach is followed in the most recent and authoritative review (Southall *et al.*, 2019).

Temporary threshold shift (TTS), 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). Southall *et al.* (2007) proposed a precautionary criterion for injury as the lowest sound exposure level capable of inducing 40 dB of TTS, which is associated with an increased risk of leaving a (small) amount of PTS, i.e. a partial hearing loss, and this recommendation was followed by Southall *et al.* (2019). The current advice regarding thresholds is reviewed in section 4 below.

3.2.3 Disturbance of behaviour

Acoustic disturbance refers to a change in the behaviour of an individual animal in response to exposure to noise. This change can be negative (eliciting fleeing and/or other anti-predator behaviours), positive (attraction, curiosity) or neutral (increased attention and orienting behaviours). In all cases, the effect of a disturbance is a change of behavioural state, which means that the cumulative effect of many disturbances, which may individually be insignificant to the well-being of the animal, is an effect on the time budget. More time is spent on the behaviours elicited by the noise and less time spent on other behaviours, including foraging, nursing offspring, socializing and resting, which in turn has an impact on the energetics of the animals. Animals that are disturbed repeatedly will have a lesser food intake and higher energy consumption, effectively reducing the resources that can be allocated to reproduction and, for endothermic mammals and birds, resources for thermoregulation (i.e., thickness of the insulating blubber layer). The ultimate effect of repeated or prolonged disturbance of individual animals is therefore a reduced survival and/or reduced reproductive success, both factors that negatively affect population development.

While the effect of acoustic disturbance ultimately is a negative impact on the vital parameters (survival and reproduction), this link is very difficult to establish empirically and agent-based models, such as the PCoD framework (New *et al.*, 2014), capable of addressing this by modelling, are still in their infancy. This means that assessments have to be based on quantifying the temporary habitat loss caused by the disturbance, i.e., quantifying the area within which animals are disturbed and include the duration of the disturbance. In order to do this, information about the lowest levels of noise exposure eliciting behavioural responses are required. Such thresholds are discussed in section 5 below.

3.2.4 Masking

Masking by noise is the reduction of listening and communication space of marine organisms due to increased levels of noise in the environment. Masking is closely related to the signal-to-noise ratio, i.e., the ratio between the intensity of a sound an animal is interested in hearing (signal) and the intensity of all other sounds (whether natural or man-made) within the same frequency band (noise) as the signal. Estimating the actual degree of masking by anthropogenic noise is complex because detailed knowledge about the masking noise, the masked signal and the distance between noise source and receiving animal is required. However, everything else being equal, increasing the ambient sound in the same frequency band as a biologically relevant signal, will lower the signal-to-noise ratio and make this signal harder to detect. Therefore, the potential for masking can be assessed by evaluating how much anthropogenic noise (in some relevant frequency band) elevates the ambient noise. As masking is virtually instantaneous, the masking noise will affect hearing almost immediately when the noise starts and the effect will cease almost immediately at the end of the noise exposure.[2] This requirement for overlap in both frequency band and time means that intermittent low frequency noise, such as pile driving noise (especially if low-pass filtered by an air bubble curtain or other sound abatement) is virtually incapable of masking the high-pitched sounds of harbour porpoises. As the pile driving noise overlaps in frequency with the underwater calls of harbour seals (Sabinsky *et al.*, 2017), there is at least the potential for masking of these calls by the pile driving noise.

3.2.5 Other effects

Other effects of chronic noise exposure include cardiovascular effects (see for example Münzel *et al.* (2020) for review of effects of traffic noise on humans) and elevated stress hormone levels (see for example Wright *et al.* (2007) for a marine mammal perspective). These effects are poorly studied in marine animals which means that there is not sufficient empirical evidence to base assessments of impact on.

3.3 Auditory frequency weighting

Animals do not hear equally well at all frequencies. This has resulted in development of auditory frequency weighting functions for different groups of marine mammals, paralleling the use of dBA-weighting in regulation of human noise exposure (Tougaard *et al.*, 2015; Houser *et al.*, 2017; National Marine Fisheries Service, 2018; Southall *et al.*, 2019). For practical reasons marine mammals have been separated into a number of functional hearing groups, reflecting differences and similarities in their hearing abilities and known susceptibility to noise (Southall *et al.*, 2019). Of these groups, two are relevant to the Baltic Sea: Phocid seals and VHF-cetaceans, which includes harbour porpoises. The corresponding weighting curves are shown in Figure 3.2.

[2] The timescale of relevance when discussing when masking starts and ends is in the order of tens to hundreds of milliseconds.

The weighting curves are used in impact risk assessments and their use means that greater emphasis is put on the energy at frequencies where the species has its best hearing. See Tougaard and Beedholm (2019) for a practical implementation.

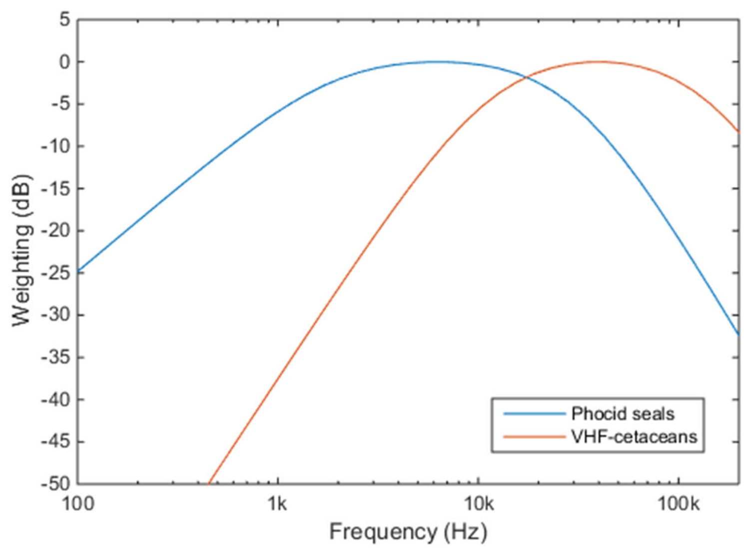

Figure 3.2. Auditory frequency weighting curves proposed by the National Marine Fisheries Service (2018) and Southall *et al.* (2019).

4 Thresholds for hearing loss

There is growing consensus on the use of noise-induced temporary hearing loss (temporary threshold shift, TTS) as a precautionary basis for establishing criteria for noise-induced injury (Southall *et al.*, 2007; Southall *et al.*, 2019). From experimentally determined thresholds for inducing minimal TTS in marine mammals, the thresholds for inducing permanent hearing loss (PTS) can be estimated by a precautionary extrapolation from the TTS-thresholds. Of relevance to the Baltic Sea and Danish Straits are the thresholds for VHF-cetaceans, which includes harbour porpoises, and phocid seals, which includes all seal species in the region. Two sets of thresholds are provided by Southall *et al.* (2019), one for so-called impulsive sounds, which includes pile driving noise and airguns, and one set for other non-impulsive sounds. The thresholds for inducing PTS by impulsive sounds are given in Table 1. These thresholds should be applied to the cumulated sound exposure level an animal is exposed to during the entire duration of the pile driving event. It may be appropriate to include fleeing behaviour of the animal when modelling the exposure to avoid the unrealistic worst-case assumption that the animal remains motionless during the entire pile driving operation (Skjellerup *et al.*, 2015).

Table 1. Lowest frequency weighted sound exposure levels considered capable of inducing permanent hearing loss (PTS) in marine mammals relevant to the Baltic Sea and Danish Straits. From Southall *et al.* (2019).

Species	Threshold	Comment
Harbour porpoise	155 dB re. 1µPa^{2}s	Weighted with the VHF auditory weighting function
Seals	185 dB re. 1µPa^{2}s	Weighted with the PCW auditory weighting function

Some authors and regulatory bodies have argued that TTS constitutes an injury and therefore should be the basis of regulation, rather than PTS, which leads to significantly stricter regulation. This is most clearly expressed in the German legislation, the so-called '*Schallschutzkonzept*' (German Federal Ministry for the Environment and Nuclear Safety, 2013) and relies on a precautionary interpretation of the EU Habitats Directive (European Commission, 1992). The choice of PTS as a basis for regulation of impact in most other countries, for example the USA (Southall *et al.*, 2007; National Marine Fisheries Service, 2018; Southall *et al.*, 2019), Denmark (Skjellerup *et al.*, 2015) and the UK (JNCC, 2010) relies on the understanding that small amounts of TTS is fully reversible (within hours of the exposure) and that the temporary hearing loss is so small that it is unlikely to have any effect on survival or reproduction.[3] See also Houser (2021) for a contemporary discussion of TTS as an injury.

[3] There are several other differences between the German regulatory framework and frameworks used in other countries, most importantly that the "Schallschütskonzept" does not include frequency weighting and cumulative exposure over repeated hammer strikes in pile driving, but it is beyond the scope of this briefing to discuss these. The main conclusion, however, is that even though TTS onset thresholds form the basis of the German regulation, the framework itself differs so much from other countries that it is not possible in a simple way to conclude that the German regulation is the more precautionary framework.

4.1 Experiments not included in Southall et al. (2019)

A substantial number of studies have been conducted in recent years in order to determine the levels of sound exposure required to induce a temporary threshold shift (TTS) in marine mammals. Studies from 2015 and before are summarised and reviewed by Finneran (2015). This review formed the empirical basis for the thresholds established by Southall *et al.* (2019). Newer studies on seals and harbour porpoises were reviewed by Tougaard (2021b), who concluded that these results, as far as pile driving and airgun noise is concerned, are fully consistent with the thresholds proposed by Southall *et al.* (2019) and listed in Table 1.

5 Thresholds for behavioural reactions

Marine mammals are known to react strongly to underwater noise, especially pulsed sounds, such as pile driving noise and airguns. Despite much experimental evidence, especially on harbour porpoises and to a lesser degree on seals, no generalized thresholds for the onset of disturbance are available. The only exception is Tougaard *et al.* (2015), which compiled evidence from observations of porpoise reactions to different types of impulsive sounds, including from pile driving, seal scarers and gill net pingers and indicated a tentative threshold for behavioural reactions 45 dB above the hearing threshold (also known as sensation level). As the hearing threshold for porpoises in the range of their best hearing (approximately 10 kHz – 150 kHz) is about 50 dB re. 1µPa, this suggests a weighted threshold around 95 dB re. µPa (figure 5.1).

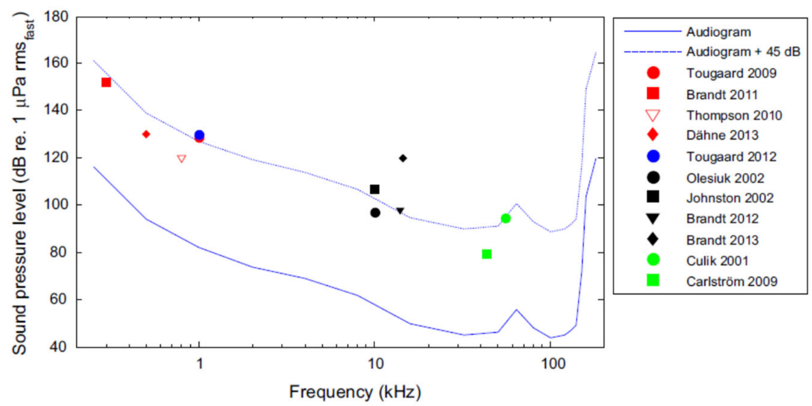

Figure 5.1. Compilation of reaction thresholds derived from a number of studies on wild porpoises. Solid line shows the audiogram of porpoises and dotted line the same audiogram offset 45 dB on the y-axis, supporting that audibility of the noise rather than the unweighted sound pressure level is the determining factor. From Tougaard *et al.* (2015).

A recent review of the available quantitative studies of reactions of harbour porpoises to pile driving noise, both actual offshore wind farm construction and playbacks at reduced levels to animals in captivity (Tougaard, 2021a) strongly indicate that porpoises start reacting negatively to pile driving noise at received levels between 95 and 110 dB re. 1 µPa ($L_{p,\,125\,ms,\,VHF}$). A threshold in this range is therefore proposed as the threshold for behavioural disturbance to porpoises when modelling noise exposure from offshore wind farm projects and conducting assessments of potential impact on porpoises from disturbance and associated temporary habitat loss.

One of the recent studies (Kastelein *et al.*, 2021) furthermore provide strong support for a frequency weighting as conjectured by Tougaard *et al.* (2015), using a curve similar to the VHF-weighting curve of Southall *et al.* (2019). In the experiment by Kastelein *et al.* (2021) pile driving noise was played back at reduced levels to a free-swimming porpoise in captivity. Six different noise signals were used, all with the same broadband level (single pulse SEL), but with different high-frequency content, created by low-pass filtering the original signal with a low-pass filter with increasingly lower cut-off frequency (figure 5.2, left). The response of the exposed animal was quantified as distance to underwater loudspeaker and respiration rate and both parameters showed a pronounced correlation with VHF-weighted SELs, thus supporting that the energy at higher frequencies are more important for eliciting behavioural reactions than are the energy at lower frequencies (Figure 5.2, right).

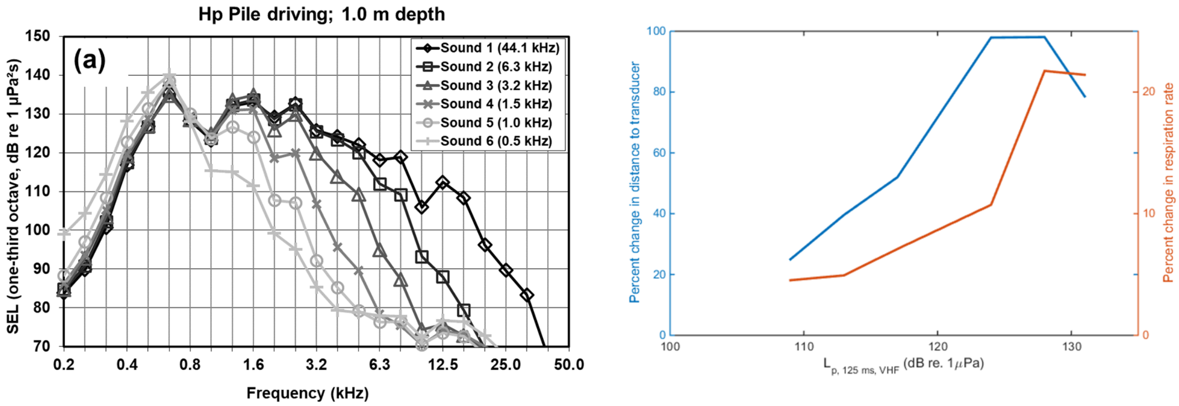

Figure 5.2. Left: Six different pile driving sounds used for playback by Kastelein *et al.* (2021), all of same single pulse SEL, but differing in the content of energy at high frequencies. Right: Response of porpoise (distance to loudspeaker and respiration rate) to playback of the six different sounds, quantified by their VHF-weighted sound pressure level. Data from Kastelein *et al.* (2021), replotted by Tougaard (2021a).

References

Amundin, M., Carlström, J., Thomas, L., Carlén, I., Koblitz, J., Teilmann, J., Tougaard, J., Tregenza, N., Wennerberg, D., Loisa, O., Kosecka, M., Kyhn, L. A., Ljungqvist, C. T., Sveegaard, S., Burt, L., Pawliczka, I., Jüssi, I., Koza, R., Arciszewski, B., Galatius, A., Jabbusch, M., Laaksonlaita, J., Lyytinen, S., Niemi, J., Šaškov, A., MacAulay, J., Wright, A., Gallus, A., Blankett, P., Dähne, M., Acevedo-Gutiérrez, A., and Benke, H. (**2021**). "Estimating the abundance of the critically endangered Baltic Proper harbour porpoise (*Phocoena phocoena*) population using passive acoustic monitoring," Authorea 10.22541/au.162755770.03327482/v1.

Bergström, L. (**2014**). "Knubbsälen i Kalmarsund. Master's thesis," (Linneuniversitetet, Kalmar).

Carlén, I., Thomas, L., Carlström, J., Amundin, M., Teilmann, J., Tregenza, N., Tougaard, J., Koblitz, J. C., Sveegaard, S., Wennerberg, D., Loisa, O., Dähne, M., Brundiers, K., Kosecka, M., Kyhn, L. A., Ljungqvist, C. T., Pawliczka, I., Koza, R., Arciszewski, B., Galatius, A., Jabbusch, M., Laaksonlaita, J., Niemi, J., Lyytinen, S., Gallus, A., Benke, H., Blankett, P., Skóra, K. E., and Acevedo-Gutiérrez, A. (**2018**). "Basin-scale distribution of harbour porpoises in the Baltic Sea provides basis for effective conservation actions," Biol. Cons. **226**, 42-53.

Dietz, R., Galatius, A., Mikkelsen, L., Nabe-Nielsen, J., Riget, F., Schack, H. B., Skov, H., Sveegaard, S., Teilmann, J., and Thomsen, F. (**2015**). "Marine mammals - Investigations and preparation of environmental impact assessment for Kriegers Flak Offshore Wind Farm," (Energinet.dk), p. 208.

European Commission (**1992**). "Council Directive 92/43/EEC of 21 May 1992 on the conservation of natural habitats and of wild fauna and flora."

Fernández, A., Edwards, J. F., Rodríguez, F., Espinosa, A., Herráez, P., Castro, P., Jaber, J. R., Martín, V., and Arbelo, M. (**2005**). ""Gas and fat embolic syndrome" involving a mass stranding of beaked whales (family Ziphiidae) exposed to anthropogenic sonar signals," Veterinary Pathology **42**, 446-457.

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.

Fredshavn, J., Nygaard, B., Ejrnæs, R., Damgaard, C., Therkildsen, O. R., Elmeros, M., Wind, P., Johansson, L. S., Alnøe, A. B., Dahl, K., Nielsen, E. H., Pedersen, H. B., Sveegaard, S., Galatius, A., and Teilmann, J. (**2019**). "Bevaringsstatus for naturtyper og arter – 2019. Habitatdirektivets Artikel 17-rapportering. Videnskabelig rapport fra Aarhus Universitet, DCE – Nationalt Center for Miljø og Energi nr. 340, 52 s.."

Galatius, A., Kinze, C. C., and Teilmann, J. (**2012**). "Population structure of harbour porpoises in the Baltic region: evidence of separation based on geometric morphometric comparisons," J. Mar. Biol. Ass. UK **92**, 1669-1676.

Galatius, A., Teilmann, J., Dähne, M., Ahola, M., Westphal, L., Kyhn, L. A., Pawliczka, I., Olsen, M. T., and Dietz, R. (**2020**). "Grey seal *Halichoerus grypus* recolonisation of the southern Baltic Sea, Danish Straits and Kattegat," Wildlife Biology.

German Federal Ministry for the Environment and Nuclear Safety (**2013**). "Konzept für den Schutz der Schweinswale vor Schallbelastungen bei der Errichtung von Offshore-Windparks in der deutschen Nordsee (Schallschutzkonzept). https://www.bfn.de/fileadmin/BfN/awz/Dokumente/schallschutzkonzept_BMU.pdf (accessed 2017/03/10).".

Hill, S. H. (**1978**). "A guide to the effects of underwater shock waves on arctic marine mammals and fish. Pacific Marine Science Report 78-26," (Patricia Bay Sidney, British Columbia).

Houser, D. S. (**2021**). "When Is Temporary Threshold Shift Injurious to Marine Mammals?," Journal of Marine Science and Engineering **9**.

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.

JNCC (**2010**). "JNCC guidelines for minimising the risk of injury and disturbance to marine mammals from seismic surveys," (Aberdeen), pp. 1-8.

Kastelein, R. A., De Jong, C. A. F., Tougaard, J., Helder-Hoek, L., and Defillet, L. N. (**2021**). "Behavioral Responses of a Harbor Porpoise (*Phocoena phocoena*) Depend on the Frequency Content of Playbacks of Pile-driving Sounds. SEAMARCO final report 2021-03 7 June 2021," (Hardewijk, the Netherlands).

Kastelein, R. A., Hoek, L., de Jong, C. A. F., and Wensveen, P. J. (**2010**). "The effect of signal duration on the underwater detection thresholds of a harbor porpoise (*Phocoena phocoena*) for single frequency-modulated tonal signals between 0.25 and 160 kHz," J. Acoust. Soc. Am. **128**, 3211-3222.

Kastelein, R. A., Wensveen, P., Hoek, L., and Terhune, J. M. (**2009**). "Underwater hearing sensitivity of harbor seals (*Phoca vitulina*) for narrow noise bands between 0.2 and 80 kHz," J. Acoust. Soc. Am. **126**, 476-483.

Ketten, D. (**1995**). "Estimates of blast injury and acoustic trauma zones for marine mammals from underwater explosions," in *Sensory systems of aquatic mammals*, edited by R. A. Kastelein, J. A. Thomas, and P. E. Nachtigall (de Spil Publishers, Woerden, the Netherlands), pp. 391-407.

Lance, R. M., and Bass, C. R. (**2015**). "Underwater blast injury: a review of standards," Diving and Hyperbaric Medicine **45**, 190-199.

Lance, R. M., Capehart, B., Kadro, O., and Bass, C. R. (**2015**). "Human injury criteria for underwater blasts," PLoS One **10**, e0143485.

Lewis, J. A. (**1996**). "Effects of underwater explosions on marine life. Report DSTO-GD-0080," (Melbourne).

Münzel, T., Kröller-Schön, S., Oelze, M., Gori, T., Schmidt, F. P., Steven, S., Hahad, O., Röösli, M., Wunderli, J.-M., Daiber, A., and Sørensen, M. (**2020**). "Adverse Cardiovascular Effects of Traffic Noise with a Focus on Nighttime Noise and the New WHO Noise Guidelines," Annual Review of Public Health **41**, 309-328.

National Marine Fisheries Service (**2018**). "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.

New, L. F., Clark, J. S., Costa, D. P., Fleishman, E., Hindell, M. A., Klanjscek, T., Lusseau, D., Kraus, S., McMahon, C. R., Robinson, P. W., Schick, R. S., Schwarz, L. K., Simmons, S. E., Thomas, L., Tyack, P., and Harwood, J. (**2014**). "Using short-term measures of behaviour to estimate long-term fitness of southern elephant seals," Mar. Ecol. Prog. Ser. **496**, 99-108.

Ryan, A. F., Kujawa, S. G., Hammill, T., Le Prell, C., and Kil, J. (**2016**). "Temporary and permanent noise-induced threshold shifts: A review of basic and clinical observations," Otol. Neurotol. **37**, e271-275.

Sabinsky, P. F., Larsen, O. N., Wahlberg, M., and Tougaard, J. (**2017**). "Temporal and spatial variation in harbor seal (*Phoca vitulina* L.) roar calls from southern Scandinavia," J. Acoust. Soc. Am. **141**, 1824-1834.

Skjellerup, P., Maxon, C. M., Tarpgaard, E., Thomsen, F., Schack, H. B., Tougaard, J., Teilmann, J., Madsen, K. N., Mikaelsen, M. A., and Heilskov, N. F. (**2015**). "Marine mammals and underwater noise in relation to pile driving - report of working group," (Energinet.dk), p. 20.

SLU Artdatabanken (**2020**). "Rödlistade arter i Sverige 2020," (Uppsala).

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.

Sveegaard, S., Galatius, A., Dietz, R., Kyhn, L., Koblitz, J. C., Amundin, M., Nabe-Nielsen, J., Sinding, M.-H. S., Andersen, L. W., and Teilmann, J. (**2015**). "Defining management units for cetaceans by combining genetics, morphology, acoustics and satellite tracking," Global Ecol Conserv **3**, 839-850.

Sveegaard, S., Nabe-Nielsen, J., and Teilmann, J. (**2018**). "Marsvins udbredelse og status for de marine habitatområder i danske farvande. Aarhus Universitet, DCE – Nationalt Center for Miljø og Energi, 36 s. - Videnskabelig rapport nr. 284."

Tougaard, J. (**2021a**). "Thresholds for behavioural responses to noise in marine mammals. Background note to revision of guidelines from the Danish Energy Agency," (Roskilde).

Tougaard, J. (**2021b**). "Thresholds for noise induced hearing loss in marine mammals. Background note to revision of guidelines from the Danish Energy Agency," (Roskilde, Denmark), p. 34.

Tougaard, J., and Beedholm, K. (**2019**). "Practical implementation of auditory time and frequency weighting in marine bioacoustics," Appl. Acoust. **145**, 137-143.

Tougaard, J., Sveegaard, S., and Galatius, A. (**2020**). "Marine mammal species of relevance for assessment of impact from pile driving in Danish waters. Background note to revision of guidelines from the Danish Energy Agency," (Roskilde).

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.Pollut.Bull. **90**, 196-208.

Verfuss, U. K., Honnef, C. G., Meding, A., Dähne, M., Mundry, R., and Benke, H. (**2007**). "Geographical and seasonal variation of harbour porpoise (*Phocoena phocoena*) presence in the German Baltic Sea revealed by passive acoustic monitoring," J.Mar.Biol.Ass.UK **87**, 165-176.

Wright, A. J., Soto, N. A., Baldwin, A., Bateson, M., Beale, C., Clark, C., Deak, T., Edwards, E., Fernandez, A., Godinho, A., Hatch, L., Kakuschke, A., Lusseau, D., Martineau, D., Romero, L., Weilgart, L., Wintle, B., Sciara, G. N. D., and Martin, V. (**2007**). "Do marine mammals experience stress related to anthropogenic noise?," Int.J.Comp.Psychol. **20**, 274-316.

Yelverton, J. T., Richmond, D. R., Fletcher, E. R., and Jones, R. K. (**1973**). "Safe distances from underwater explosions for mammals and birds," (Albuquerque, New Mexico).

Young, G. (**1991**). "Concise methods for predicting the effects of underwater explosions on marine life. Report NAVSWC MP 91-220 " (Silver Spring, MD).