Defence, Safety & Security
Oude Waalsdorperweg 63
2597 AK Den Haag
P.O. Box 96864
2509 JG The Hague
The Netherlands

www.tno.nl

T +31 88 866 10 00

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Wozep underwater sound: frequency sensitivity of porpoises and seals

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Author(s) Christ de Jong
Sander von Benda-Beckmann

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Samenvatting

In het '*Wind op Zee Ecologisch Programma*' (*Wozep*) wordt onderzoek uitgevoerd naar de kennisleemtes rond de (cumulatieve) ecologische effecten van windenergie op zee. Deze studie is gericht op de onzekerheid in de beoordeling van de effecten van het heigeluid in de aanlegfase van een windpark op zeezoogdieren (bruinvis en twee soorten zeehonden). De studie adresseert de volgende onderzoeksvragen:

1 Is de bruinvis inderdaad gevoeliger voor verstoring door heigeluid dan gewone en grijze zeehonden?

2 Kan de onzekerheid in de beoordeling van de effecten van het heigeluid op zeezoogdieren worden verminderd door rekening te houden met de frequentie-afhankelijkheid van het gehoor van de dieren ('frequentie-weging')?

Deze vragen worden behandeld in de door Rijkswaterstaat georganiseerde Werkgroep Zeezoogdieren en Onderwatergeluid, uitgaande van de in dit rapport beschreven informatie. Dit rapport beschrijft de resultaten van:

1. Literatuurstudie en analyse van de beschikbare informatie over de toepasbaarheid van frequentieweging in de beoordeling van de gevoeligheid van bruinvissen en zeehonden voor nadelige effecten van impulsief (hei)geluid.
2. Numerieke analyse van het effect van de diverse vormen van frequentieweging op de beschikbare geluidspectra van heigeluid, zoals die gemeten zijn op zee en in de bassins van Seamarco, als ook berekend zijn met de Aquarius modellen én toegepast zijn bij het bepalen van drempelwaarden voor effectbeoordeling.

Contents

1 Introduction

This study is part of the research programme *Wozep* (‘*Wind op Zee Ecologisch Programma*’), which investigates the ecological effects of offshore wind energy development in The Netherlands. It addresses the following research questions:

3. Is it correct to assume that harbour porpoises are more sensitive to the underwater sounds produced by piling for the offshore wind turbine foundations in the North Sea than harbour and grey seals?
4. Is there a need to incorporate in the impact assessment the frequency spectrum of the piling sound in relation to the frequency sensitive hearing of porpoises and seals? What are the consequences of frequency weighting for the threshold values for hearing loss and behavioural response?
5. Are the available acoustic models sufficiently accurate to incorporate the frequency weighting in the impact assessment? If not, how can uncertainty be reduced?

These questions will be addressed by a Dutch national expert group on underwater noise, organized by Rijkswaterstaat. TNO was asked to prepare this report as input for the working group meetings.

The following approach has been followed:

1. A review of the available literature on the application of frequency weighting in the assessment of the impact of underwater sound on harbour porpoise (*Phocoena phocoena*), harbour seal (*Phoca vitulina*) and grey seal (*Halichoerus grypus*).
2. A numerical analysis on the available data from measurements and calculations of piling sound, to evaluate the effects of different forms of frequency weighting on impact assessment and threshold levels

The current version of this report presents the results of the literature review and data analysis. A first attempt to answer the research questions is made in chapter 5. Knowledge gaps and proposals for further research are addressed in Chapter 6.

Figure 1 Harbour porpoise, harbour seal and grey seal (source: Wikipedia).

2 Assessing effects of piling sound on harbour porpoises and seals

The current guideline for environmental impact assessments and appropriate assessments for future Dutch Offshore Wind Energy projects [Heinis & de Jong, 2015] includes a comparison of the calculated levels of piling sound to which porpoises and seals are potentially exposed against threshold levels above which avoidance behaviour or noise induced hearing loss are expected to occur.

In agreement with the assumption made in the Interim PCoD model [Harwood et al., 2014], which is used to determine the population consequences of acoustic disturbance, a ‘significant behavioural response’ is defined as a behaviour with a score of 5 or higher on the behaviour response severity scale in [Southall et al., 2007]; According to this severity scale, these are behaviours such as changes in swimming behaviour and breathing, avoiding a particular area and changes in vocal behaviour (for the purposes of communications and foraging). In [Heinis & de Jong, 2015], acoustic threshold values for avoidance behaviour were based on observed reductions in harbour porpoise presence around the piling location during the construction of the Borkum West II wind farm and on observations of jumping out of the water (porpoises) and haul-out (seals) during exposure studies in the pools of SEAMARCO.

To assess the occurrence of effects on the hearing sensitivity of harbour porpoises and seals threshold values are used for the occurrence of a temporary or permanent increase in the hearing threshold: TTS (temporary threshold shift) and PTS (permanent threshold shift) respectively.

Given the state of knowledge at the time of development of the guideline, the threshold values for the harbour porpoise do not take hearing sensitivity as a function of the frequency into account. In the case of the seal, in line with [Southall et al., 2007], Mpw-weighted sound exposure level threshold values have been used, with ‘pw’ standing for ‘pinnipeds in water’. Southall et al. [2007] provide one weighting function for pinnipeds in water. In [NMFS, 2016] different weighting functions are provided for phocid pinnipeds (earless seals, or ‘true seals’) and otariid pinnipeds (eared seals: sea lions and fur seals), using ‘PW’ for phocid pinnipeds in water and ‘OW’ for otariid pinnipeds in water.

Since the development of the Dutch guideline, further research has led to evidence that supports taking frequency sensitivity into account in the impact assessment [Tougaard et al., 2015, Finneran, 2015, Wensveen, 2016]. Earlier suggestions in this direction [Verboom & Kastelein, 2005, Nedwell et al., 2006] lacked convincing evidence at that time. Based on the new findings, the US National Marine Fisheries Service has incorporated marine mammal auditory weighting functions in its technical guidance for assessing the effects of anthropogenic sound on marine mammal hearing [NMFS, 2016]. It should be noted that this technical guidance is limited to the onset of noise induced hearing loss (TTS and PTS) due to cumulative exposure to either impulsive (e.g., airguns, impact pile drivers) or non-impulsive (e.g., tactical sonar, vibratory pile drivers) sounds and it does not consider avoidance behaviour.

In an “Assessment of impact of underwater clearance of historical explosives by the Royal Netherlands Navy on harbour porpoises in the North Sea” [von Benda-Beckmann et al., 2015a], it was chosen not to apply frequency weighting to the SEL when estimating the risk of TTS and PTS for explosions. However, an inverted audiogram weighting (the ‘P-filter’) was applied for computing the sound dosage for predicting behavioural disturbance to explosion sound.

The ‘Update for SAKAMATA risk thresholds for harbour porpoises’ [von Benda-Beckmann and de Jong, 2015] also presents frequency dependent risk thresholds for TTS and PTS, for implementation in the SAKAMATA risk management tool that is used by the Royal Netherlands Navy as part of their policy to manage and mitigate the effects of sonar on marine mammals.

The main question for the current study is whether the impact assessments and appropriate assessments for future Dutch Offshore Wind Energy projects can be improved by incorporating frequency weighting. If so, what are the appropriate weighting functions, for hearing effects and avoidance behaviour caused by exposure of harbour porpoises and seals to piling sounds? And what are the corresponding weighted threshold values for avoidance behaviour or noise induced hearing loss?

In addition, it is of interest to consider whether the same weighting functions and threshold values can be applied for the assessment of the effects of other impulsive sound sources, such as underwater explosions and airguns for seismic exploration.

2.1 Acoustic metrics

Different metrics are being used to characterize the impulsive underwater sound generated by piling strikes. Following the recently developed ISO standards for underwater acoustic terminology [ISO 18405, 2017] and for the measurement of radiated underwater sound from percussive pile driving [ISO 18406, 2017] (here and throughout this report) the relevant metrics for the sound pressure are:

1. Sound exposure level (or ‘time-integrated squared sound pressure level’); symbol $L_{E,p}$
   - Single strike sound exposure level (SEL_{ss}) for an individual acoustic pulse; symbol $L_{E,\mathrm{ss}}$
   - Cumulative sound exposure level (SEL_{cum}) for a defined period of time, which includes multiple acoustic pulses; symbol $L_{E,\mathrm{cum}}$
2. Peak sound pressure level (or ‘zero-to-peak sound pressure level’); symbol $L_{p,\mathrm{pk}}$
3. Mean-square sound pressure level (or ‘root-mean-square sound pressure level’, or ‘sound pressure level’; SPL);, averaged over the duration (T_{90}) of the signal; symbol L_p

Figure 2 gives an example of a recorded piling signal, illustrating the quantities underlying these metrics. The duration of the impulsive sound is given by the selection of a sub-window that contains 90 % of the total exposure (time-integrated squared sound pressure). The start and end times of this sub-window (t_5 and t_{95}) are determined by the moments at which the cumulative exposure reaches 5 % and 95 % of the total exposure.

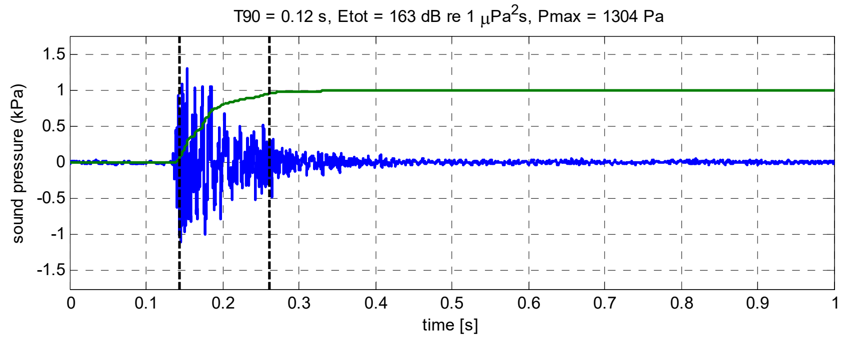

Figure 2 Example of the acoustic pressure received at a hydrophone for a single hammer strike (blue line), from [de Jong & Ainslie, 2012]. The green line gives the time-integrated squared sound pressure as a function of time (scaled to an arbitrary reference level). The thick black dashed lines indicate the t_5 and t_{95} start and end times of the T_{90} (T90) duration of the signal. The peak sound pressure (Pmax = p_{pk}) is defined as the maximum of the absolute value of the pressure signal within the T_{90} window in the complete frequency bandwidth of the recording (here 3 Hz to 102.4 kHz) The sound exposure level (Etot = L_E) quantifies the total energy in the T_{90} window.

ISO 18405 also defines 'weighted' variants of the sound pressure level and sound exposure level, which incorporate a frequency weighting function, for example representing a specified frequency-dependent characteristic of hearing sensitivity in a particular type of animal. In the common practice for the analysis of sound effects in relation to hearing, sound pressure and sound exposure level spectra are often reported in a proportional frequency bandwidth of one tenth of a decade (approximately equal to one third of an octave). Auditory weighting functions are then applied to the band levels.

The first criteria for marine mammal noise exposure were recommended by [Southall et al., 2007]. The new NMFS guidance [NMFS, 2016] follows [Southall et al., 2007] by using dual metric threshold values for the risk of TTS and PTS due to impulsive sounds, one for cumulative sound exposure level ($L_{E,\mathrm{cum,w}}$), where the 'w' refers to the application of a generalized frequency weighting function for specified groups of marine mammals, and one for (unweighted) peak sound pressure level ($L_{p,\mathrm{pk}}$).

The current Dutch guideline provides threshold values for the risk of TTS and PTS in harbour porpoises and seals due to cumulative sound exposure level received by swimming animals as a result of the driving of an entire pile. For the harbour porpoise, given the data from [Lucke et al., 2009] and [Kastelein et al., 2013], unweighted broadband $L_{E,\mathrm{cum}}$ threshold values are used, that do not take hearing sensitivity as a function of the frequency into account. In the case of the seal, M_{pw}-weighted values are taken from [Southall et al., 2007], with 'pw' standing for '(phocid) pds in water'.

Southall et al. [2007] adopted a dual-criterion approach (for $L_{p,\mathrm{pk}}$ and $L_{E,\mathrm{ss,M\text{-}weighted}}$) to determine behavioural criteria for a single pulse exposure, based on TTS-onset as a proxy for significant behavioural disturbance. For other anthropogenic sound types (multiple pulses and non-pulses) they were "unable to derive explicit and broadly applicable numerical threshold values for delineating behavioural disturbance”. They have provided a severity scale for behavioural responses observed in either field or laboratory conditions and tables in which published response data are scored, using the received sound pressure level (averaged over the signal duration) as acoustic metric. They recognize that the relationship between the acoustic level and the severity of the behavioural response is generally very weak and arguably strongly dependent on contextual variables and of the acoustic similarities between the anthropogenic sound and biologically meaningful natural signals.

In spite of the difficulties, the population consequences of behavioural disturbance due to piling sound are considered to be more relevant than these associated with the risk of TTS and PTS, which probably affects a very limited number of animals. In 2012, the EU technical subgroup on underwater noise for the Marine Strategy Framework Directive suggested that indicator 11.1.1 for low and mid frequency impulsive sounds primarily addresses behavioural change that causes parts of marine animal habitats to become temporarily unavailable [Dekeling et al., 2014]. Therefore the Dutch guideline provides tentative threshold values for behavioural disturbance, quantified as a level 5 score on the scale of [Southall et al. 2007]. To account for the short duration of the piling sounds (typically 50 to 250 ms) the threshold values are set for the sound exposure level as a result of a single piling strike ($L_{E,\mathrm{ss}}$), unweighted for porpoises and M_{pw}-weighted for seals.

All of the above mentioned metrics involve a uniform time weighting, in the appropriate time window. Tougaard et al. [2015] suggest the application of noise criteria based on a time-weighted metric that they call ‘$L_{eq\text{-}fast}$’. This metric includes an exponential averaging of the impulsive sound with a 125 ms time constant, which is assumed to approximate the integration process and integration time of marine mammal hearing as well as human hearing, see the discussion in §2.3. In addition, they apply a frequency weighting based on a measured porpoise audiogram. This proposed metric is loosely based on the output of the sound level meters used in air acoustics, but Tougaard et al. [2015] do not use the terminology as used in the IEC 61672 standard. In the terminology of the IEC standard, the metric proposed by Tougaard et al. would be called a ‘time-weighted sound level’. The ‘equivalent continuous sound level’ (or ‘time-averaged sound level) in the IEC standard does involve frequency weighting, but no time-weighting.

A similar time and frequency weighting (‘loudness’) concept was applied to assess the potential behavioural effects of underwater explosions at the North Sea on porpoises, in [von Benda-Beckmann et al. 2015a].

2.2 Auditory frequency weighting

Auditory frequency weighting functions are applied in noise impact assessment in humans and marine mammals, to account for frequency dependent sensitivity of the hearing system. This frequency dependence varies with the level of the sound that is presented to the ears.

Houser et al. [2017] present a review of the history, development and application of auditory weighting functions in humans and marine animals. While human auditory weighting functions are used for the assessment of various effects (annoyance, masking, hearing loss), the development of auditory weighting functions for marine mammals is currently mainly aimed at the assessment of the risk of noise-induced hearing loss (TTS onset). Houser et al. argue that “it remains unknown as to whether and to what degree the various marine mammal weighting functions can be suitably applied to effects other than noise-induced hearing loss, such as noise-induced behavioural disturbance and masking”. They provide a list of recommendations for studies that that would need to be carried out to validate the application of weighting functions in the estimation of acoustic impact on marine mammals resulting from noise exposure and to increase the robustness of the suggested weighting functions.

Southall et al. [2007] proposed the use of so-called ‘M-weighting functions’ for five groups of cetaceans and phocid pinnipeds. These functions are described by the equation:

$$W(f) = 10\log_{10}\left[\frac{R(f)}{\max R(f)}\right]^2 \text{ dB} \qquad (1)$$

Where $R(f) = \frac{f_{high}^2 f^2}{(f_{low}^2+f^2)(f_{high}^2+f^2)}$

The parameters for harbour porpoises and seals are given in Table 1.

Table 1 Southall et al. [2007] M-weighting parameters for porpoises and seals.

North Sea species	Species group	filter	f_{low}	f_{high}
Harbour porpoise	High frequency cetacean	M_{HF}	200 Hz	180 kHz
Harbour seal; grey seal	Phocid pinnipeds in water	M_{PW}	75 Hz	75 kHz

Recently, the US National Marine Fisheries Service (NMFS) has proposed the use of updated marine mammal auditory weighting functions, in its technical guidance for assessing the effects of underwater anthropogenic (human-made) sound on the hearing of marine mammal species [NMFS, 2016]. These have been developed by Finneran, based on the latest scientific literature. They were derived using data on hearing ability (composite audiograms), effects of noise on hearing, and data on equal latency. These functions are described by the equation:

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

The parameters for harbour porpoises and seals are given in Table 2.

Table 2 NMFS [2016] weighting parameters for porpoises and seals.

North Sea species	Species group	a	b	f_1	f_2	C
Harbour porpoise	HF	1.8	2	12 kHz	140 kHz	1.36 dB
Harbour seal; grey seal	PW	1	2	1.9 kHz	30 kHz	0.75 dB

The auditory weighting functions are compared in Figure 3. This illustrates that the ‘updated’ frequency weighting proposed by NMFS has a stronger filtering effect than the original M-filters from [Southall et al., 2007].

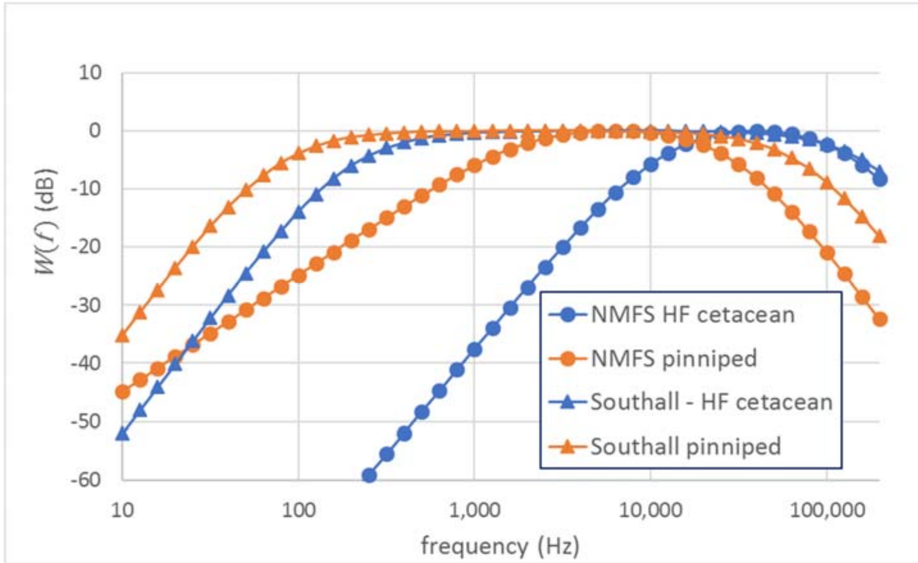

Figure 3 auditory weighting functions for porpoises and seals from [Southall et al., 2007] and [NMFS, 2016].

The NMFS auditory weighting functions are derived from composite audiograms that have been obtained from the available measurements for the different species groups, in combination with the available data from studies on 'equal loudness' and 'equal latency' and on available TTS onset data. See [NMFS, 2016] for the details of how these were derived.

NMFS [2016] describes an 'acoustic exposure function' $E(f)$, which is proportional to the inverse of the auditory weighting function:

$$E(f) = K - 10\log_{10}\left[\frac{\left(\frac{f}{f_1}\right)^{2a}}{\left(1+\left(\frac{f}{f_1}\right)^2\right)^a\left(1+\left(\frac{f}{f_2}\right)^2\right)^b}\right] \text{ dB} \quad (3)$$

This describes a frequency dependent threshold the onset of TTS dependent on the appropriate value of gain parameter K, see Table 3. All other parameters are the same as in eq.(2). To illustrate how the auditory weighting functions relate to auditory acoustic thresholds, Table 3 provides an estimated gain parameter for 'hearing threshold'.

Table 3 NMFS [2016] threshold parameters for porpoises and seals.

North Sea mammal species	group	'Hearing threshold' K	TTS onset K
		dB re 1 μPa^2	dB re 1 μPa^{2}s
Harbour porpoise	HF	48	152
Harbour seal; grey seal	PW	53	180

The resulting 'hearing threshold' exposure functions and the composite audiograms are compared against measured tonal audiograms for a harbour porpoise [Kastelein et al., 2010] and two harbour seals [Kastelein et al., 2009] in Figure 4.

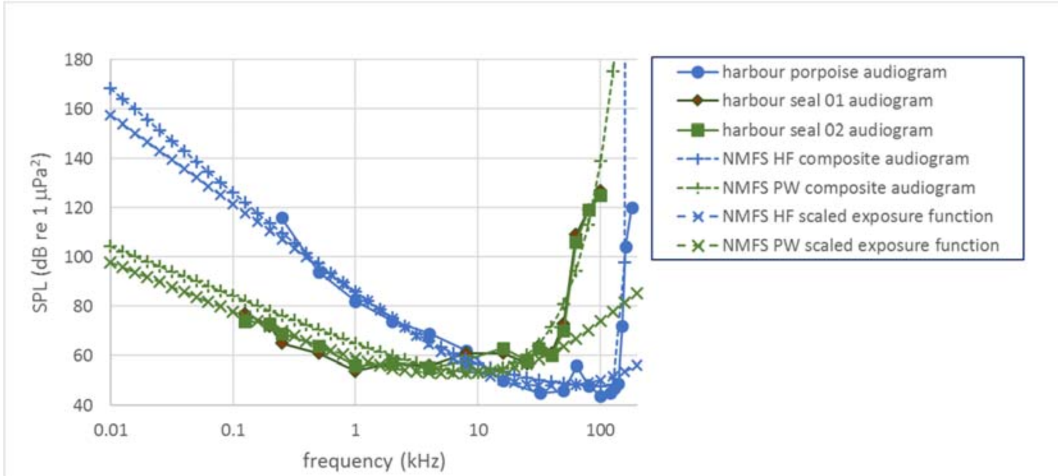

Figure 4 NMFS [2016] exposure functions at the hearing threshold (x) and composite audiograms (+) for HF cetaceans and phocid pinnipeds in water, compared with the audiograms for a harbour porpoise [Kastelein et al., 2010] and two harbour seals [Kastelein et al., 2009], measured for tonal signals of 1.7 s duration.

Figure 4 illustrates that the NMFS weighting functions are closely related to the audiograms of porpoises and seals. The exposure functions are lower than the audiograms at the upper end of the frequency range. NMFS [2016] states: "This is important to note because the weighting/exposure functions are derived not just from data associated with the composite audiogram but also account for available TTS onset data". This will not affect the assessment of the broadband levels of low-frequency impulsive sounds, such as these from marine piling, explosions or seismic exploration. It can be seen in Figure 4 that at frequencies below about 5 kHz the NMFS exposure function for phocid pinnipeds closer matches with the measured seal audiograms than the composite audiogram for phocid pinnipeds.

Porpoise hearing studies at SEAMARCO have provided further evidence that weighting of the received sound with the tonal audiogram (with an appropriate time-weighting) can be used to predict the audibility of complex signals, such as frequency sweep [Kastelein et al., 2011d] and impulsive sounds [Kastelein et al., 2012c]. Additional analysis of the results of the data of the studies of the audibility of playbacks of impulsive sounds [Kastelein et al., 2012c], mimicking an underwater explosion sound ('detonation pulse'), and of pile driving sounds [Kastelein et al., 2013] provide further evidence. The unweighted broadband SEL at the hearing threshold (60 dB re 1 $\mu Pa^2 s$) for the detonation pulse was significantly lower than that for the piling sounds (72 and 74 dB re 1 $\mu Pa^2 s$ respectively). This difference can be explained from the different frequency contents of the two pulse types, see Figure 5. With application of the NMFS high frequency cetacean weighting, the weighted broadband SEL at the hearing threshold for the detonation pulse was equal to that for the piling sounds (41 dB re 1 $\mu Pa^2 s$).

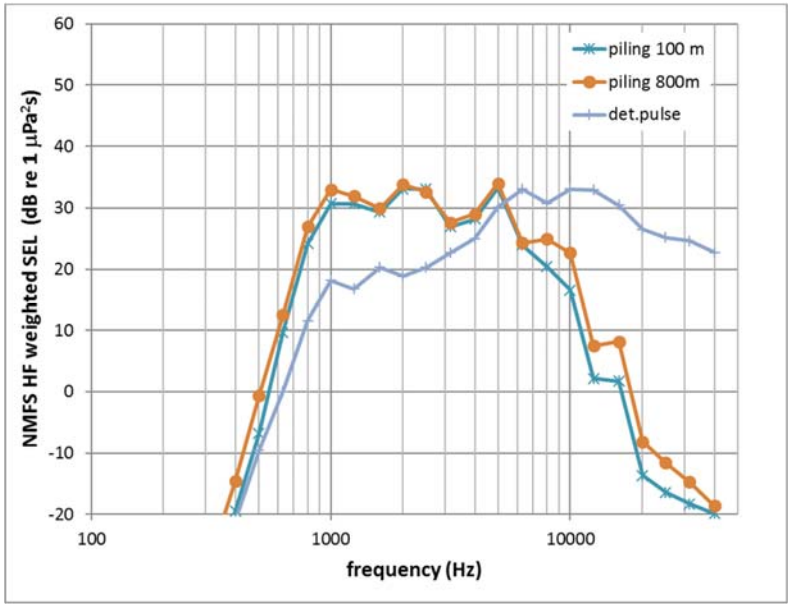

Figure 5 NMFS HF (high frequency cetacean) weighted SEL spectra of the playback detonation pulse [Kastelein et al., 2012c] and piling sounds Kastelein et al., 2013], corresponding with the unweighted broadband SEL at the 50 % hearing threshold.

2.3 Auditory time weighting

Tougaard et al. [2015] propose the use of an exponential time weighting, similar to the ‘fast’ (F) weighting used in sound level meters for airborne sound [IEC 61672-1, 2013], to ensure that measures of sound exposures of different exposure studies are comparable (see also §2.1). The ‘fast average’ time-weighted sound pressure level $L_{p,\mathrm{F}}$ can be calculated from the unweighted sound pressure level $L_{p,T}$, averaged over the pulse duration T:

$$L_{p,\mathrm{F}} = L_{p,T} + 10\log_{10}\left[1 - \mathrm{e}^{-T/\tau}\right]\ \mathrm{dB} \tag{4}$$

where τ is the time constant of the exponential filter. The ‘fast average’ in sound level meters for human noise exposure [IEC 61672-1, 2013] implies a time constant τ of 125 ms. Tougaard et al. [2015] argue that the limited available data for the time constant of marine mammal hearing show a ‘reasonably good consistency with human data’, and hence propose to use the same 125 ms time constant for porpoises. This argument is underpinned by an analysis of the results of measurements by Kastelein et al. [2010] of the hearing threshold of a harbour porpoise for single frequency-modulated tonal signals as a function of signal duration. The data are reproduced in Figure 6. The left graph in Figure 7 shows that the audiograms are indeed overlaying after application of the exponential time-weighting (eq.4).

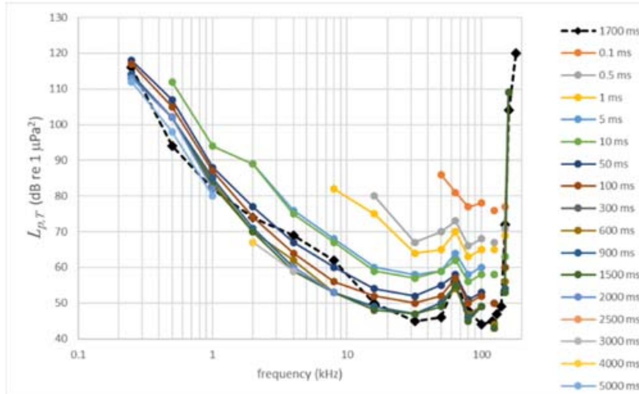

Figure 6 Harbour porpoise audiograms for frequency-modulated tonal signals of various duration, from [Kastelein et al., 2010], expressed in terms of the level $L_{p,T}$ of the mean square sound pressure averaged over the signal duration T. The black dashed line (1700 ms duration) is for the results of measurements in 2002, in which the signals were probably masked by background noise for frequencies between 1 and 20 kHz.

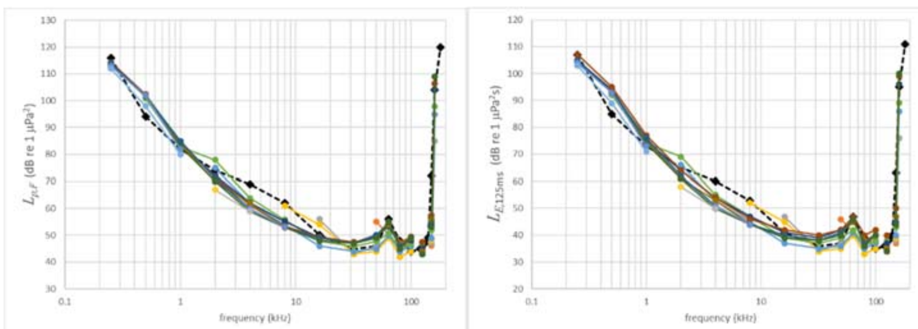

Figure 7 Harbour porpoise audiograms for frequency-modulated tonal signals of various duration (see Figure 6 for legend), expressed in terms of the ‘fast’ weighted sound pressure level $L_{p,\mathrm{F}}$ (left graph) and in terms of the sound exposure level $L_{E,125\mathrm{ms}}$ over a maximum integration time of 125 ms (right graph).

Alternatively, single strike exposure level has been proposed in [Heinis & de Jong, 2015] as a metric for marine mammal behavioural response to impulsive sounds. The right graph in Figure 7 demonstrates that the audiograms expressed in this metric are overlaying, similar to those that were expressed in terms of the fast-weighted sound pressure level, provided that the integration time for the sound exposure is maximized at the τ=125 ms time constant[1]:

$$L_{E,\tau} = L_{p,T} + 10\log_{10}\left[\frac{\min(T,\tau)}{1\ \mathrm{s}}\right]\mathrm{dB} \qquad (5)$$

Tougaard et al. [2015] chose to neglect the finding by Kastelein et al. [2010 and 2010a] that the time constant of the hearing of porpoises and seals is frequency dependent, with the argument that the data show reasonably good consistence with human data, where this frequency dependence is also neglected. For seals the time constant appears to be nearly inversely proportional to the frequency, corresponding to about 780 periods of the tonal sounds. This suggests that the τ=125 ms time constant is mainly applicable for frequencies around 6 kHz.
For lower frequencies the time constant is probably longer.

[1] Because $\min(T/\tau, 1)$ (eq.5) provides a good first order approximation to $1 - e^{-T/\tau}$ (eq.4).

The T_{90} duration of marine piling noise signals, for example these measured from the piling for the Gemini wind farm [Binnerts et al., 2016], varies between about 75 ms at 732 m from the pile to about 580 ms at 32 km. Maximizing the integration time to 125 ms would result in a broadband SEL_{ss} that is $10 \log_{10}[580/125]\ \mathrm{dB} \approx 7\ \mathrm{dB}$ lower than the SEL_{ss} integrated over the total pulse duration at 32 km. The real effect is somewhat more complicated because the frequency content in the pulses changes over the pulse duration due to dispersion in the shallow water channel, see Binnerts et al. [2016].

Though the [Kastelein et al., 2010] data suggest that the audibility of the pulses (in quiet conditions) is not increased by the extra duration of the pulses after the integration time τ, this does not necessarily imply that the extra duration does not contribute to the porpoise's avoidance response at higher exposure levels. The avoidance behaviour occurs at sound exposure levels far above the hearing threshold. It is unknown how the signal duration affects the behavioural response at these exposure levels. As a precautionary approach, the total SEL_{ss} of an individual pulse is used for the assessment of the avoidance response, and not a (lower) SEL_{ss} limited to the 125 ms integration time.

2.4 Uncertainty and parameters

The current Dutch guideline for environmental impact assessments and appropriate assessments for future Dutch Offshore Wind Energy projects relies on single number acoustic criteria for noise induced hearing loss and behavioural disturbance. The main benefit of the many assumptions underlying this approach is that it enables a quantitative comparison between various scenario's, allowing industry and regulators to decide on the appropriate wind turbine foundation locations, the appropriate time for installation and the application of the appropriate noise mitigation measures. On the other hand, the quantitative results from this simplified approach may lead to an incorrect impression of accuracy. The many knowledge gaps and the very limited amount of data suggest that the results are still largely uncertain.

The assessment of the impact of underwater sound exposure on marine mammals involves many parameters. These are associated with the effects that are being considered, within the context in which exposure occurs as well as with the many characteristics of the sounds to which the animals are exposed. These parameters are discussed below. They have to be taken into account when comparing the results of various studies in the literature of the impact of impulsive noise on porpoises and seals.

2.4.1 Noise induced hearing loss

In this context, noise induced hearing loss is described in terms of the onset of a temporary or permanent hearing threshold shift (TTS and PTS).

- TTS-onset is defined by a tonal (or narrowband) hearing threshold shift of +6 dB (or greater), measured at a short time (1-4 minutes) after the exposure has ended, for one or more specific hearing frequencies.
- PTS would imply that such a threshold shift does not recover over time after the exposure. Since that is hard to measure, PTS is presumed to be likely if a threshold shift ≥ 40 dB is measured [Southall et al., 2007].

2.4.2 *Behavioural disturbance*

The Dutch guideline includes an application of the interim PCoD model [Harwood et al., 2014] to estimate the population consequences of acoustic disturbance. This Interim PCoD model defines ‘significant behavioural response’ as a behaviour with a score of 5 or higher on the behaviour response scale from [Southall et al.., 2007]; these are behaviours such as changes in swimming behaviour and breathing, avoiding a particular area and changes in vocal behaviour (for the purposes of communications and foraging). This behaviour is considered to be equivalent to the ‘avoidance behaviour’ for which the acoustic threshold values for porpoises and seals were developed. The Southall et al. [2007] severity scale (or an updated version of this scale) can be used for a like with like comparison of published behavioural responses.

2.4.3 *Context*

The behavioural response of marine mammals to sound exposure arguably depends on the context in which the exposure takes place [Southall et al., 2007, Ellison et al., 2012].
A first distinction must be made between the behavioural response of free-ranging animals versus animals in captivity. Southall et al. [2007] provide different severity scoring scales for these two conditions.
Behavioural responses can differ greatly among individual animals and may strongly depend on factors such as age, gender, group composition, previous experience and activity (feeding, mating, migrating, etc.).
Masking of the sound exposure by ambient noise may significantly reduce the severity of the behavioural response, see e.g. [Kastelein et al., 2011]. Moreover, the ‘acoustic scene’ to which the sound exposure is added may influence the behavioural response. Aspects like related sounds, multi-path propagation effects and source movement may provide the animals with clues concerning the size and nature of the sound source, and hence affect its behavioural response. Animals may become habituated to recurring sounds and can learn to associate specific sounds (e.g. the sound from acoustic deterring devices) with the presence of prey (the ‘dinner bell’ effect [Jefferson & Curry, 1996]).

2.4.4 *Sound characteristics*

As suggested by Southall et al. [2007], a distinction must be made between sound types. They distinguish ‘single pulses’, ‘multiple pulses’ and ‘non-pulses’, though they acknowledge that the distinction is not always clear. The piling for offshore wind turbine foundations can be categorized as ‘multiple pulses’. The use of airgun arrays for seismic exploration falls in the same category, to usually at a much lower pulse repetition rate (tens of seconds versus ~ one second).
Other characteristics of impulsive sounds are the frequency content and the pulse duration. These may change with distance from the source, under influence of underwater propagation conditions, especially in shallow water. If the duration of the signal changes because of propagation conditions (i.e. if the sharp pulse is smeared out) it may be possible that it no longer qualifies as a ‘pulse’ [Southall et al. 2007]. For ‘multiple pulses’ sounds also the duty cycle is of importance.
Southall et al. [2007] state that the presence or absence of acoustic similarities between the anthropogenic sound and biologically relevant natural signals in the animal’s environment (e.g., calls of conspecifics, predators, prey) is important as well.

Many of these ‘other’ sound characteristics are not described by the single number acoustic criteria for noise induced hearing loss and behavioural disturbance. Hence, the applicability of dose-response relationships observed for one sound to other sound exposures is generally uncertain.

3 Effects of frequency weighting on piling noise levels

If frequency weighting would be introduced in the assessment of the impacts of piling noise on porpoises and seals, what would be the consequence for the threshold values for hearing loss and behavioural response?

3.1 Marine piling noise measurement data

Figure 8 shows typical examples of spectra of unweighted single strike sound exposure level from the piling for wind turbine foundations in the North Sea. Measurements from marine piling projects for North Sea wind farms show similar spectral characteristics, with the highest unweighted sound exposure levels around 100 Hz.

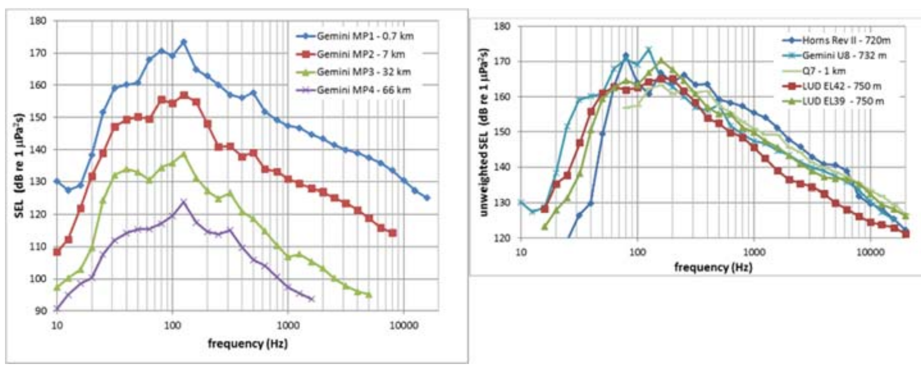

Figure 8 One-third octave band spectra of mean unweighted single strike sound exposure levels. Left graph: measured at 4 distances from pile U8 for the Gemini wind farm, from [Binnerts et al., 2016]. The upper part of the frequency range is omitted for the distant locations, because this was dominated by background noise. Right graph: measured at 0.7 to 1 km from different North Sea piling projects: Horns Rev II in Denmark [Brandt et al., 2011] and Princess Amalia wind farm (‘Q7’), Gemini and Luchterduinen (‘LUD’) in the Netherlands [Binnerts et al., 2016].

Figure 9 shows the SEL spectra after application of the auditory weighting functions for porpoises and seals from [NMFS, 2016].

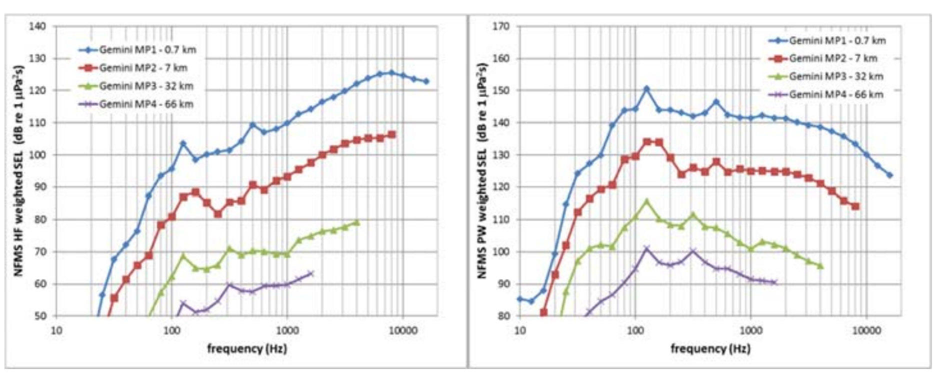

Figure 9 One-third octave band spectra of single strike sound exposure level as measured during piling for the Gemini wind farm (pile U8), from [Binnerts et al., 2016], after application of the NMFS [2016] weighting for high frequency cetaceans (HF, left figure) and phocids in water (PW, right figure).

This shows that the weighting for porpoises (HF) emphasizes the higher frequencies (> 1 kHz). Since these were dominated by background noise for the distant locations, the high frequency content of the weighted spectra cannot be determined from the measurements at the distant locations, and hence the estimation of the broadband SELss (the sum over all frequency bands) of the piling signals at these distances is incomplete and hence uncertain. At these distances, background noise will mask the observation of piling sounds by porpoises.
The weighting for seals (PW) also increases the contribution of higher frequencies, leading to flatter spectra.

Table 4 presents the broadband values of the single strike sound exposure level, unweighted and with application of the auditory weighting functions for porpoises and seals from [Southall et al., 2007] and [NMFS, 2016].

Table 4 unweighted and weighted broadband values of single strike sound exposure level as measured during piling for the Gemini wind farm (pile U8).

	unit	MP1	MP2	MP3	MP4
distance	km	0.7	7	32	66
Unweighted SEL_{ss}	dB re 1 $\mu Pa^2 s$	178	163	144	128
Southall M_{HF} weighted SEL_{ss}	dB re 1 $\mu Pa^2 s$	167	152	132	119
NMFS HF weighted SEL_{ss}	dB re 1 $\mu Pa^2 s$	133	112	84	67
Southall M_{PW} weighted SEL_{ss}	dB re 1 $\mu Pa^2 s$	174	159	140	125
NMFS PW weighted SEL_{ss}	dB re 1 $\mu Pa^2 s$	157	141	121	107

The frequency weighted broadband values are clearly lower than the unweighted values, but since the SEL values with different frequency weightings are different metrics, it is not useful to compare the level differences. The measured SEL levels should be evaluated against the appropriate (weighted and unweighted) threshold levels for behavioural disturbance and hearing threshold shifts, see §3.4.

3.2 Data from piling noise calculations

TNO's Aquarius models are currently applied in impact assessments for offshore piling activities. The model calculations were recently validated against measurement data [Binnerts et al., 2016] from piling for the Gemini wind farm.
It was found that the Aquarius 1.0 calculations tend to underestimate the SEL at lower frequencies (below 400 Hz), but overestimate the SEL at the higher frequencies at larger distances from the pile, see Figure 10.

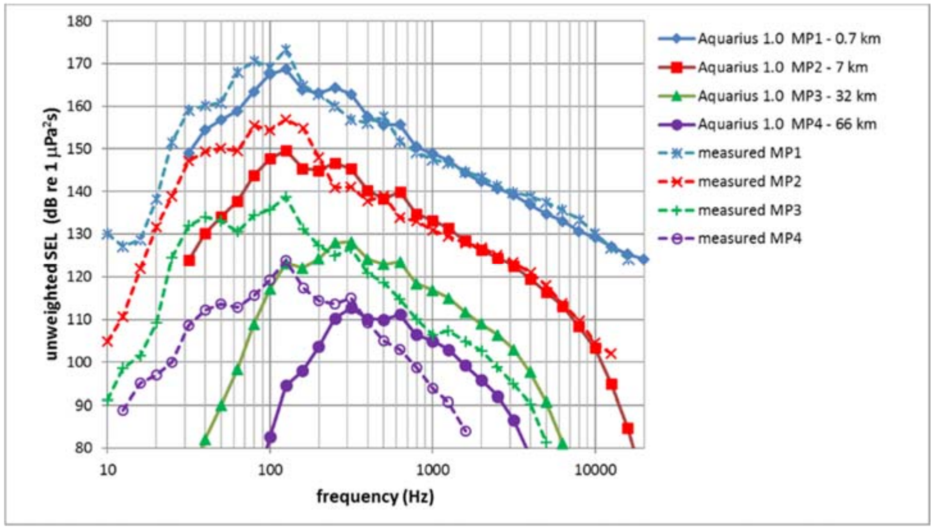

Figure 10 Aquarius 1.0 model–data comparison of the SEL at four distances from pile U8 of the Gemini wind farm, after [Binnerts et al., 2016]. The measurement results have been corrected for background noise, by subtracting the mean sound exposure of the background noise over the pulse duration from the piling sound exposure.

Figure 11 shows the calculated SEL spectra after application of the auditory weighting functions for porpoises and seals from [NMFS, 2016].

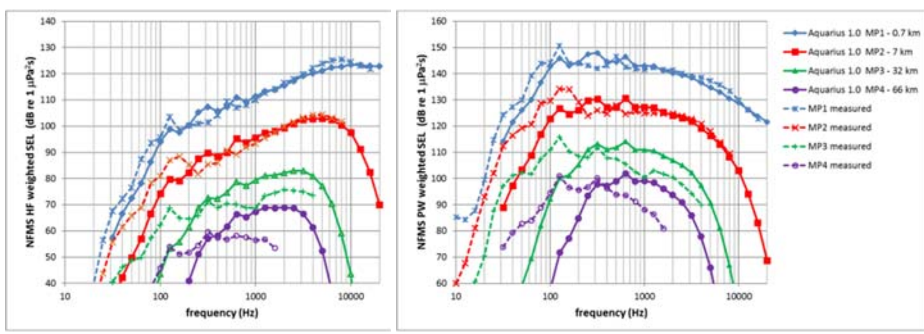

Figure 11 One-third octave band spectra of single strike sound exposure level as calculated (♦) and measured (o) for the piling for the Gemini wind farm (pile U8), from [Binnerts et al., 2016], after application of the NMFS [2016] weighting for high frequency cetaceans (HF, left figure) and phocids in water (PW, right figure).

This illustrates the importance of the spectral distribution that underlies the broadband levels. The shape of the spectrum varies with increasing distance from the pile, under influence of sound propagation effects. Hence the frequency bandwidth that dominates the broadband SEL varies with distance and with the applied frequency weighting.

Table 5 presents the measured and calculated broadband values of the single strike sound exposure level, as calculated and measured, unweighted and with application of the auditory weighting functions for porpoises and seals from [NMFS, 2016].

Table 5 unweighted and weighted broadband values of single strike sound exposure level as measured and calculated for the piling of Gemini pile U8, see also Table 4.

			MP1	MP2	MP3	MP4
	distance	km	0.7	7	32	66
	Calculated unweighted SEL_{ss}	dB re 1 μPa^{2}s	174	156	134	119
	Measured unweighted SEL_{ss}	dB re 1 μPa^{2}s	178	163	144	128
	Unweighted measured - calculated	dB	+4	+7	+10	+9
porpoise	Calculated NMFS HF SEL_{ss}	dB re 1 μPa^{2}s	132	111	91	77
	Measured NMFS HF SEL_{ss}	dB re 1 μPa^{2}s	133	112	84	67
	NMFS HF measured - calculated	dB	+1	+1	-7	-10
seal	Calculated NMFS PW SEL_{ss}	dB re 1 μPa^{2}s	156	139	122	108
	Measured NMFS PW SEL_{ss}	dB re 1 μPa^{2}s	157	141	121	107
	NMFS PW measured - calculated	dB	+1	+2	-1	-1

This shows that the observed differences between the measured and calculated spectra varies with distance, but more importantly it varies with the applied frequency weighting function. The difference between measured and calculated unweighted broadband SEL is fully dominated by the differences at low frequencies (below 400 Hz). The differences at these low frequencies become insignificant after application of the NMFS weighting, in particular for the 'HF' weighting for porpoises (Figure 11), but also for seals.

The Aquarius1.0 calculations underestimate the measured unweighted SEL_{ss}, so that an assessment on the basis of these unweighted levels appears to underestimate the effects on marine mammal hearing and behaviour. However, when the NMFS frequency weighting functions are applied, the differences between the measured and predicted levels are smaller. The predictions overestimate the porpoise-weighted levels at greater distance from the pile (MP3 and MP4).

3.3 Data from laboratory playback studies

The studies at SEAMARCO in which seals and porpoises were exposed to pile driving playback sounds [Kastelein et al., 2011, 2013, 2015] provided input data for the current Dutch guideline for environmental impact assessment [Heinis & de Jong, 2015]. However, the spectral characteristics of the playback sounds peak at higher frequencies than these of marine piling sounds in the field, see Figure 12.

The unweighted broadband SEL associated with the two spectra in Figure 12 are nearly equal, but the frequency weighted SEL of the piling playback sound is 15 to 22 dB higher than that of the field measurements, see Figure 13 and Table 6.

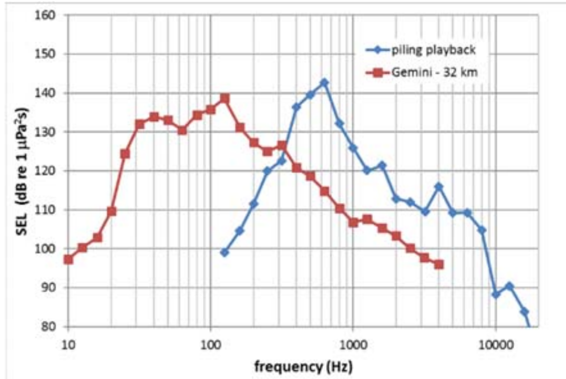

Figure 12 One-third octave band spectrum of the unweighted single strike sound exposure level from measurements at SEAMARCO with pile driving playback sounds, broadband L_E = 145 dB re 1 μPa²s [Kastelein et al., 2015], compared with the spectrum from measurements at about 32 km from a pile during the piling for Gemini, broadband L_E = 144 dB re 1 μPa²s (see Figure 8).

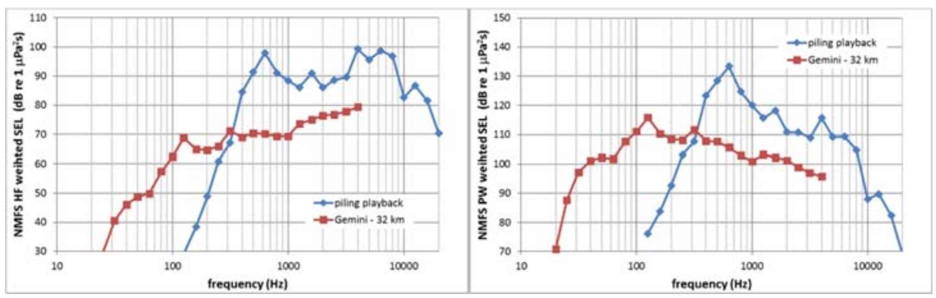

Figure 13 One-third octave band spectrum of the NMFS [2016] frequency weighted single strike sound exposure levels from Figure 12. Left graph: porpoise (HF) weighting, right graph: seal (PW) weighting.

Table 6 unweighted and weighted broadband values of single strike sound exposure level measurements of pile driving playback sounds and of pile driving sounds and sounds measured at 32 km from piling for the Gemini wind farm at approximately the same broadband SEL_{ss}.

		Playback at SEAMARCO	Gemini piling at 32 km
Unweighted SEL_{ss}	dB re 1 μPa²s	145	144
NMFS HF weighted SEL_{ss}	dB re 1 μPa²s	106	84
NMFS PW weighted SEL_{ss}	dB re 1 μPa²s	136	121

3.4 Threshold values for effects on porpoises and seals

The measured SEL values must be evaluated against the appropriate (weighted and unweighted) threshold levels for behavioural disturbance and hearing threshold shifts. Currently applied and proposed threshold levels are summarized in Table 7. A direct comparison of the decibel values in Table 7 is not meaningful, since these refer to different weighted and unweighted quantities.

Table 7 Published threshold levels for behavioural disturbance and hearing threshold shifts.

species	effect	reference	metric	dB re 1 $\mu Pa^2 s$
porpoise	avoidance	[Heinis & de Jong, 2015]	Unweighted SEL_{ss}	140
	TTS-onset	[Heinis & de Jong, 2015]	Unweighted SEL_{cum}	164
		[Southall et al., 2007]	M_{HF} weighted SEL_{cum}	183
		[NMFS, 2016]	HF-weighted SEL_{cum}	140
	PTS-onset	[Heinis & de Jong, 2015]	Unweighted SEL_{cum}	179
		[Southall et al., 2007]	M_{HF} weighted SEL_{cum}	198
		[NMFS, 2016]	HF-weighted SEL_{cum}	155
seal	avoidance	[Heinis & de Jong, 2015]	M_{PW} weighted SEL_{ss}	145
	TTS-onset	[Heinis & de Jong, 2015]	M_{PW} weighted SEL_{cum}	171
		[Southall et al., 2007]	M_{PW} weighted SEL_{cum}	171
		[NMFS, 2016]	PW-weighted SEL_{cum}	170
	PTS-onset	[Heinis & de Jong, 2015]	M_{PW} weighted SEL_{cum}	186
		[Southall et al., 2007]	M_{PW} weighted SEL_{cum}	186
		[NMFS, 2016]	PW-weighted SEL_{cum}	185

3.5 Application to the Gemini measurement data

Table 8 provides an example of the assessment of the exposure of a static animal (porpoise/seal) at 32 km (MP3) from the piling for Gemini pile U8.

The thresholds for TTS and PTS are expressed in terms of SEL_{cum}. A total number of 3361 hammer strikes was used for the installation of Gemini pile U8. Assuming that each strike resulted in approximately the same SEL_{ss}, a static animal would be exposed to a SEL_{cum} value for the installation that is about $10 \log_{10}(3361)\ \mathrm{dB} \approx 35\ \mathrm{dB}$ above the value of SEL_{ss}.

This demonstrates how the different assessments can lead to rather different conclusions, for example:

- According to the current Dutch [Heinis & de Jong, 2015] approach (without frequency weighting), the static porpoises (‘worst case’) suffer from a great risk of TTS (and nearly PTS) at this distance (exposure 15 dB above threshold).
- According to the Southall et al. [2007] criteria (M_{HF} weighting and a higher threshold value) there is no risk of TTS for these porpoises (exposure 16 dB below threshold).
- And according to the NMFS [2016] criteria (HF weighting) this risk is even lower (19 dB below threshold).

Table 9 gives the example for a static animal (porpoise/seal) at 7 km (MP2) from the same pile. Also at this distance, the risk of TTS/PTS is lower according to the (frequency weighted) NMFS [2016] criteria, than to the other two assessments.

Table 8 Single strike and cumulative, unweighted and weighted sound exposure levels for a static animal at 32 km (MP3) during the 3361 hammer strikes for pile U8 in the Gemini wind farm and the difference with the threshold levels for behavioural disturbance and TTS from Table 7. The red coloured cells indicate where the thresholds are exceeded.

species	effect	reference	metric	dB re 1 μPa^2s	dB above threshold
porpoise	avoidance	[Heinis & de Jong, 2015]	Unweighted SEL_{ss}	144	+4
	TTS-onset	[Heinis & de Jong, 2015]	Unweighted SEL_{cum}	179	+15
		[Southall et al., 2007]	M_{HF} weighted SEL_{cum}	167	-16
		[NMFS, 2016]	HF-weighted SEL_{cum}	121	-19
	PTS-onset	[Heinis & de Jong, 2015]	Unweighted SEL_{cum}	179	0
seal	avoidance	[Heinis & de Jong, 2015]	M_{PW} weighted SEL_{ss}	140	-5
	TTS-onset	[Heinis & de Jong, 2015]	M_{PW} weighted SEL_{cum}	175	+4
		[Southall et al., 2007]	M_{PW} weighted SEL_{cum}	175	+4
		[NMFS, 2016]	PW-weighted SEL_{cum}	156	-14
	PTS-onset	[Heinis & de Jong, 2015]	M_{PW} weighted SEL_{cum}	175	-11

Table 9 Single strike and cumulative, unweighted and weighted sound exposure levels for a static animal at 7 km (MP2) during the 3361 hammer strikes for pile U8 in the Gemini wind farm and the difference with the threshold levels for behavioural disturbance and TTS from Table 7. The red coloured cells indicate where the thresholds are exceeded.

species	effect	reference	metric	dB re 1 μPa^2s	dB above threshold
porpoise	avoidance	[Heinis & de Jong, 2015]	Unweighted SEL_{ss}	163	+23
	TTS-onset	[Heinis & de Jong, 2015]	Unweighted SEL_{cum}	198	+34
		[Southall et al., 2007]	M_{HF} weighted SEL_{cum}	187	+23
		[NMFS, 2016]	HF-weighted SEL_{cum}	148	+8
	PTS-onset	[Heinis & de Jong, 2015]	Unweighted SEL_{cum}	198	+19
		[Southall et al., 2007]	M_{HF} weighted SEL_{cum}	198	0
		[NMFS, 2016]	HF-weighted SEL_{cum}	148	-7
seal	avoidance	[Heinis & de Jong, 2015]	M_{PW} weighted SEL_{ss}	159	+14
	TTS-onset	[Heinis & de Jong, 2015]	M_{PW} weighted SEL_{cum}	194	+23
		[Southall et al., 2007]	M_{PW} weighted SEL_{cum}	194	+23
		[NMFS, 2016]	PW-weighted SEL_{cum}	176	+6
	PTS-onset	[Heinis & de Jong, 2015]	M_{PW} weighted SEL_{cum}	194	+8
		[Southall et al., 2007]	M_{PW} weighted SEL_{cum}	194	+8
		[NMFS, 2016]	PW-weighted SEL_{cum}	176	-9

Since there are no measurements available of porpoises or seals that experienced hearing threshold shifts after exposure to piling sound at sea, a direct validation of these assessments cannot (yet) be made.

4 Data for noise impact on porpoises and seals

To support a decision about the potential application of frequency-weighting functions in the impact assessment, the literature has been surveyed for relevant data and observations. To facilitate the comparison between the results of various studies, an overview has been made of the main parameters for each data set:

1. Species (harbour porpoise or harbour/grey seal)
2. Effect (TTS/PTS onset or behavioural response scoring ≥ 5 on the Southall et al. [2007] severity scale))
3. Free-ranging animals or laboratory subjects
4. Sound type (single pulse or multiple pulses)
   - Pile driving (actual or playback)
   - Airguns (single or array, actual or playback)
   - Explosion
   - Acoustic deterrent (actual or playback)
   - Naval sonar (CW and FM sweeps, playback)
5. Frequency range (centre frequency and –10 dB bandwidth)
6. Pulse duration (T_{90}), inter-pulse interval and exposure duration (or number of pulses)

To evaluate the benefits of applying frequency-weighting in the impact assessment, one would want to compare weighted and unweighted threshold levels for similar effects on the same species for different pulse types with different frequency ranges, for similar temporal parameters (duty cycle, duration).

This chapter is organised in two main sections, for porpoises and seals, with subsections for the different effects (TTS/PTS onset and behavioural response).

4.1 Harbour porpoises

4.1.1 Auditory effects

The first evidence of noise induced hearing loss (TTS) in a harbour porpoise was published in [Lucke et al., 2009]. Since then several TTS studies on porpoises have been published by SEAMARCO [Kastelein et al., 2011-2017]. In addition, Popov et al. [2011] measured TTS in a closely related species, the Yangtze finless porpoise (*Neophocaena asiaeorientalis*). Table 10 provides an overview of the relevant publications. Most of these have been taken into account in [Finneran, 2015; Tougaard et al., 2105; NMFS, 2016], except for the most recent ones.

In the context of impact assessment [Heinis et al., 2015; NMFS, 2016] TTS-onset is usually defined by a tonal (or narrowband) hearing threshold shift of +6 dB (or greater), at one or more specific hearing frequencies, measured at a short time (1-4 minutes) after the exposure has ended. Noise induced threshold shifts tend to occur at or above the frequency of the noise exposure, with a tendency to shift towards higher frequencies with increasing exposure level [Finneran, 2015; Kastelein 2014a].

Table 10 Available data for TTS in harbour porpoises (updated from [NMFS, 2016]). The data of the Kastelein et al. studies are obtained by a behavioural method.

nr	Reference	Sound source	comment
1	Lucke et al., 2009	Single airgun sound	AEP method
2	Popov et al., 2011	Half-octave band noise (32, 45, 64 and 128 kHz), 3 min pulses	Yangtze finless porpoise; AEP method
3	Kastelein et al., 2011	continuous noise and playbacks of pile driving sounds	
4	Kastelein et al., 2012	Octave-band noise (4 kHz)	
5	Kastelein et al., 2013a	1.5 kHz tone	
6	Kastelein et al., 2014	1-2 kHz sweeps	Effect of duration and inter-pulse interval
7	Kastelein et al., 2014a	6-7 kHz sweeps	Frequency of threshold shift
8	Kastelein et al., 2014b	6.5 kHz tone	
9	Kastelein et al., 2015	Playbacks of pile driving sounds	
10	Kastelein et al., 2015c	6-7 kHz sweeps	Intermittent and continuous
11	Kastelein et al., 2016	Playbacks of pile driving sounds	Effect of exposure duration
12	Kastelein et al., 2017a	Multiple airgun sounds	

Several attempts have been made [Tougaard et al., 2015; Finneran, 2015; von Benda-Beckmann & de Jong, 2015; Wensveen, 2016; NMFS, 2016] to derive frequency dependent threshold levels for the sound exposure at which TTS-onset is likely to occur, based the limited available data. These attempts are complicated by the observation [von Benda-Beckmann & de Jong, 2015] that the threshold shifts are not only influenced by the frequency of the sound to which the animals are exposed, but also to other parameters such as the bandwidth, the duration and the duty cycle. Moreover, the results of the studies cannot all be directly compared because of the use of different methods to determine the threshold shift (AEP and behavioural) and differences in time delay between the exposure and the measurement of the threshold shift. And further uncertainty is introduced by the derivation of the TTS-onset from the measured levels of threshold shift at different hearing frequencies that are reported in the different studies.

Nevertheless, NMFS [2016], convinced of frequency dependent TTS onset by studies on bottlenose dolphins [Finneran & Schlundt, 2013], used the limited available data to propose a frequency dependent TTS onset threshold for high-frequency cetaceans (the solid line in Figure 14, referred to as ‘exposure function’). This is mainly based on studies for continuous sound exposure (octave band noise and sonar signals, from studies 4 to 7 in Table 10). In [von Benda-Beckmann & de Jong, 2015], various assumptions were made to derive a frequency dependent TTS onset threshold for harbour porpoises exposed to intermittent sonar sounds (duty cycle 10 %), adapted from the equal latency weighting functions as determined by Wensveen et al. [2014] and the weightings proposed in [Finneran & Jenkins, 2012]. The sonar data suggested that the SEL threshold level for TTS-onset associated with a 10 % duty cycle was about 8 dB higher than that for a continuous (100 % duty cycle) exposure.

Recent studies of TTS induced by pile driving playback sounds [Kastelein et al. 2015; 2016] and by multiple airgun sounds [Kastelein et al., 2017a] seem to support the application of frequency weighting. Figure 15 shows that the frequency bands with the maximum (NMFS HF) weighted SELcum overlap with the frequencies at which TTS occurred for exposure to impulsive sounds from airguns and playbacks of piling sounds with rather different (unweighted) spectra.

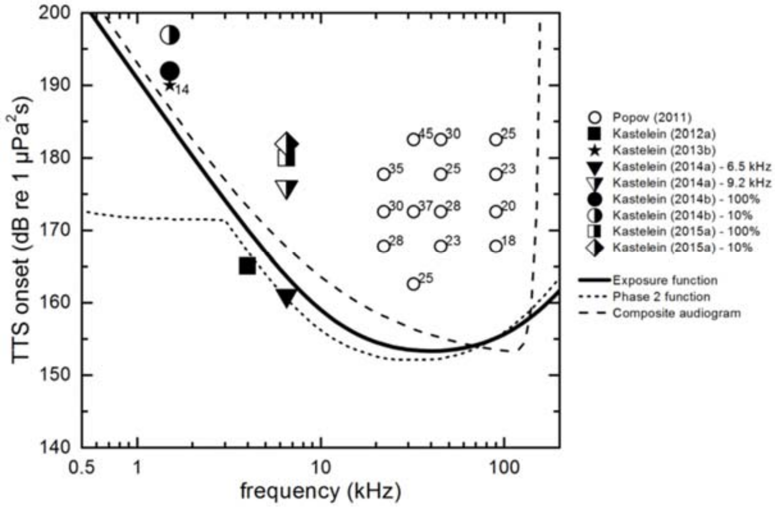

Figure 14 High-frequency cetacean TTS exposure function, (normalized) composite audiogram, and Phase 2 exposure functions compared to high-frequency cetacean TTS data. Large symbols with no numeric values indicate onset TTS exposures. Smaller symbols represent specific amounts of TTS observed, with numeric values giving the amount (or range) or measured TTS. Filled and half-filled symbols — behavioural data. Open symbols — AEP data; Fig. A19 from [NMFS, 2016].

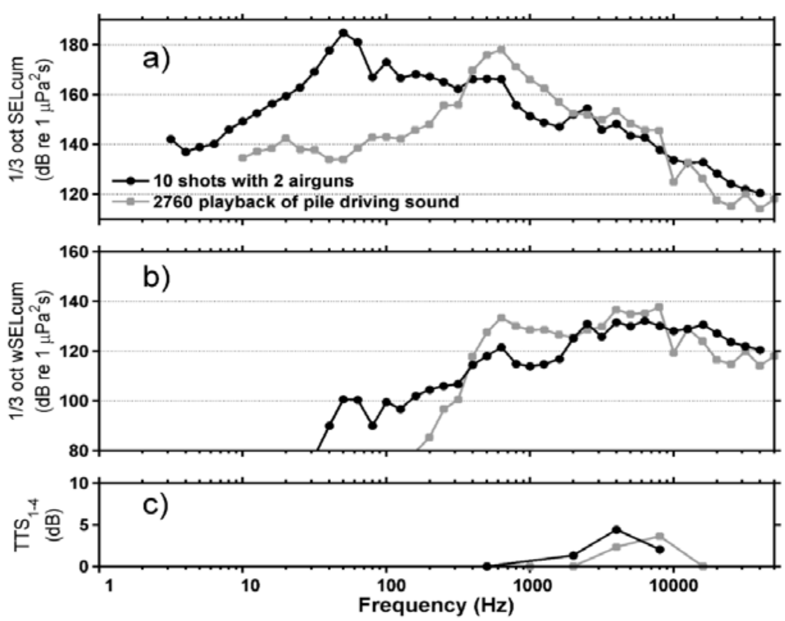

Figure 15 a) Unweighted decidecade (ddec) SELcum spectra of 10 double airgun shots (shot interval: ~ 17 s), and of 2760 pile driving playbacks (inter-pulse interval 1.3 s) during a 120 min exposure [Kastelein et al.. 2015]. b) Measured frequency-weighted ddec wSELcum spectra from both studies, using the NMFS [2016] weighting function for harbour porpoises. c) Observed mean TTS_{1-4} for different test frequencies (0.5, 1, 2, 4, and 8 kHz); from [Kastelein et al., 2017a].

Table 11 summarizes the available data of TTS in harbour porpoises induced by exposure to low frequency impulsive sounds. In spite of the many differences that make a direct comparison questionable, this suggests that the frequency weighted SELcum threshold for TTS-onset (140 dB re 1μPa²s) as proposed by NMFS [2016], see Table 7, gives a better indication of the risk than the unweighted SELcum threshold (165 dB re 1μPa²s) from Lucke's study, that is applied in the current Dutch piling noise risk assessment.

Table 11 Overview of available data of TTS in harbour porpoises after exposure to low frequency impulsive sounds.

study	exposure	Unweighted SELcum	NMFS HF weighted SELcum	Threshold shift A: AEP B: behavioural
Lucke et al., 2009	Single airgun shot	165 dB re 1 μPa²s	140 dB re 1 μPa²s	$TTS_{16\text{-}18min,A}$ 20 dB (at 4 kHz)
Kastelein et al., 2015	2760 pile driving playback sounds	180 dB re 1 μPa²s	144 dB re 1 μPa²s	$TTS_{1\text{-}4s,B}$ 3.6 dB (at 8kHz).
Kastelein et al., 2017	10 double airgun shots	188 dB re 1 μPa²s	140 dB re 1 μPa²s	$TTS_{1\text{-}4s,B}$ 4.4 dB (at 4 kHz)

4.1.2 PTS onset

PTS onset acoustic thresholds for marine mammals have not been directly measured and must be extrapolated from available TTS onset measurements. Based on limited available marine mammal impulsive data, and terrestrial mammal threshold shift growth rates [NMFS, 2016] decided to set the PTS onset acoustic thresholds for impulsive sound exposure at 15 dB above the threshold for TTS. The auditory frequency weighting functions in [NFMS, 2016] are applicable for the assessment of the risk of TTS as well as PTS.

In an 'update for SAKAMATA risk thresholds for harbour porpoises' in relation to Navy sonar [von Benda-Beckmann & de Jong, 2015] it was concluded from data from exposure studies at Seamarco [Kastelein et al., 2014&2015c] that the implied frequency dependence for PTS risk onset is much smaller than for the TTS onset. Figure 16 shows of the underlying data and the resulting TTS and PTS threshold values for harbour porpoises and other high frequency cetaceans exposed to intermittent sonar sound.

Based on limited available marine mammal impulsive data, the NMFS [2016] report advises to use the relationships previously derived in Southall et al.. (2007), which relied upon terrestrial mammal growth, to predict PTS onset. Comparison of this approximate 15 dB difference between TTS and PTS onset acoustic thresholds in the SELcum metric with the published data of measured TTS growth (Figure 17) confirms that this leads to a precautionary estimation of the PTS exposure threshold for impulsive sounds. The spectra in Figure 16 suggest a much larger difference between the TTS and PTS thresholds for intermittent sonar sound, in combination with a different shape of the spectrum for the TTS and PTS thresholds. However, the PTS threshold spectra proposed by NMFS are more precautionary than the SAKAMATA risk curves. Therefore it is proposed to use the NMFS thresholds in the assessment of PTS due to of impulsive sounds.

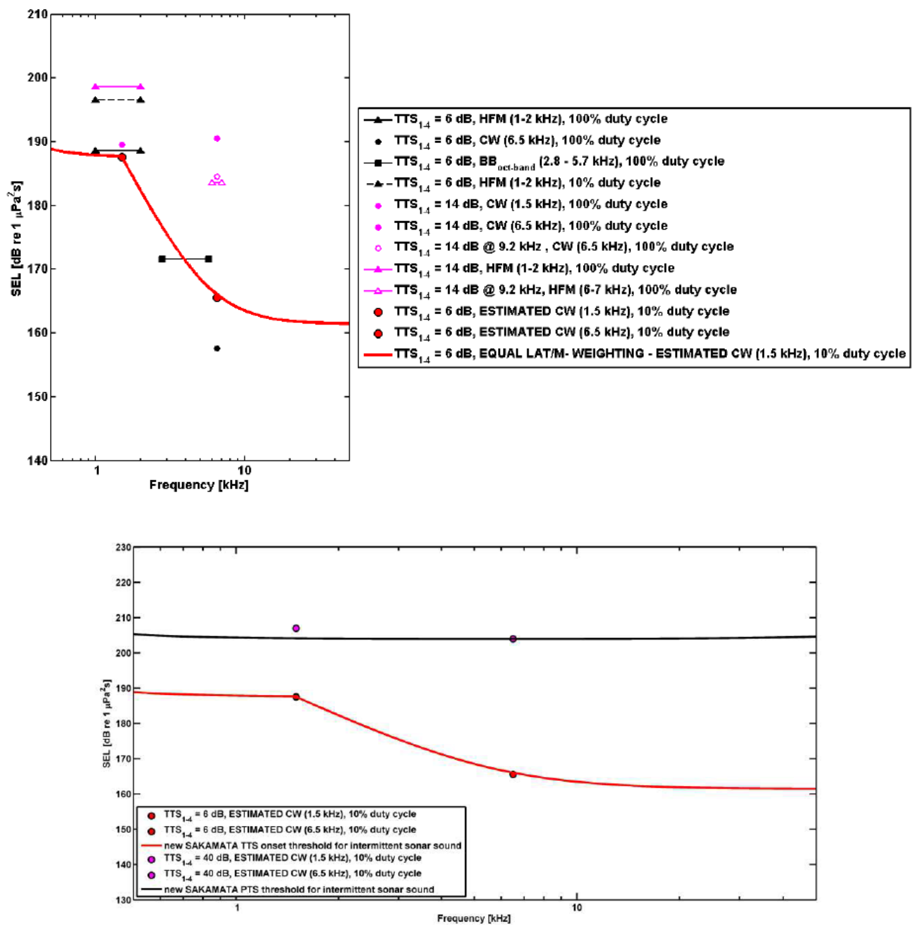

Figure 16 Top: Data point measured by SEAMARCO for sonar exposures for TTS onset (6 dB; black symbols), and higher levels of TTS (14 dB TTS; magenta symbols). The sonar exposures were selected to have the same duration (1 hour), but had different signal waveforms (CW, FM and BB noise), and were transmitting continuously (100% duty cycle), or intermittently (10% duty cycle). Bottom: The solid lines represent the new SAKAMATA v3 frequency dependent thresholds for TTS onset (red) and PTS risk onset (black) for harbour porpoises and other high frequency cetaceans exposed to intermittent sonar sound. The circles are the best estimates for SEL thresholds for PTS risk onset (magenta circles) and TTS onset, (red circles) for harbour porpoises. Figure from [von Benda-Beckmann & de Jong, 2015].

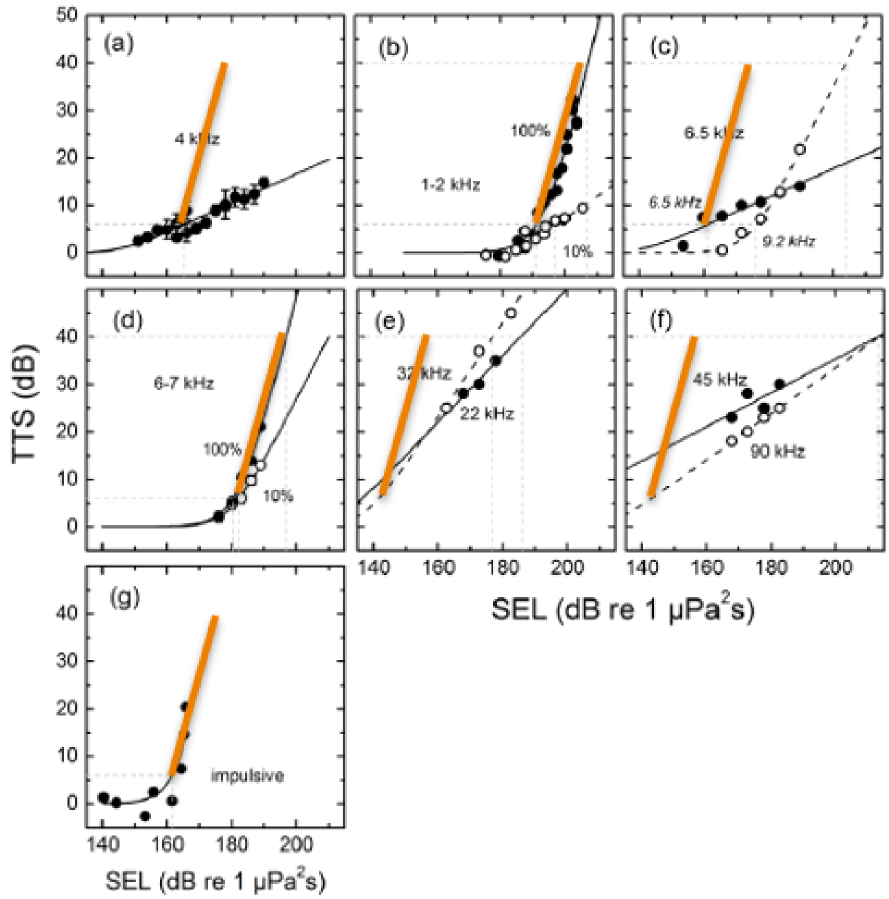

Figure 17 Measured TTS growth curves for high frequency cetaceans (mainly harbour porpoises) from {NMFS 2016]. The orange straight lines overlay the trend that corresponds with the growth from 6 dB (TTS) to 40 dB (PTYS) threshold shift for an increase of the SEL with 15 dB, as assumed in the derivation of the PTS threshold.

4.1.3 *Behavioural disturbance*

Different types of behavioural response of harbour porpoises have been documented for different anthropogenic sound sources. The first studies were for acoustic deterrent and harassment devices (pingers [Culik et al., 2001; Kastelein et al., 2006b, 2008 & 2008a; Carlström et al., 2009] and scarers [Olesiuk et al., 2002; Brandt et al., 2012 & 2013, Kastelein et al., 2015a; Mikkelsen et al., 2017]), intended to keep mammals away from fishing nets, fish farms and piling sites. Subsequent studies were for underwater acoustic data transmission systems [Kastelein et al., 2005], naval sonars [Kastelein et al., 2012b, 2013c & 2015c], marine piling [Tougaard et al., 2009 & 2012; Brandt et al., 2011 & 2016; Dähne et al., 2013; Kastelein et al., 2013; Graham et al., 2017], ships [Hermannsen et al., 2014; Dyndo et al., 2015] and seismic airguns [Thompson et al., 2013].

In their review of auditory weighting functions, Houser et al. [2017] argue that “it remains unknown as to whether and to what degree the various marine mammal weighting functions can be suitably applied to effects other than noise-induced hearing loss, such as noise-induced behavioural disturbance and masking”. Nevertheless, Tougaard et al. [2015], von Benda-Beckmann et al.. (2015) and Wensveen [2016] argue that the available data indicate that there is a correlation between the behavioural response of harbour porpoises and the level above the hearing threshold (also referred to as the ‘sensation level’) of the sound exposure, which suggests that the weighted level would provide a more robust metric for behavioural response than unweighted levels. This sounds reasonable, but there is actually very little data to support this hypothesis.

One way of comparing the results of the various behavioural response studies for different types of sound is proposed by Tougaard et al. [2015] and Wensveen [2016]. For this purpose, the threshold levels at which avoidance (or similar) behaviour is observed are converted to the time-weighted $L_{p,F}$ metric and plotted as a function of the centre frequency (and bandwidth), see Figure 18.

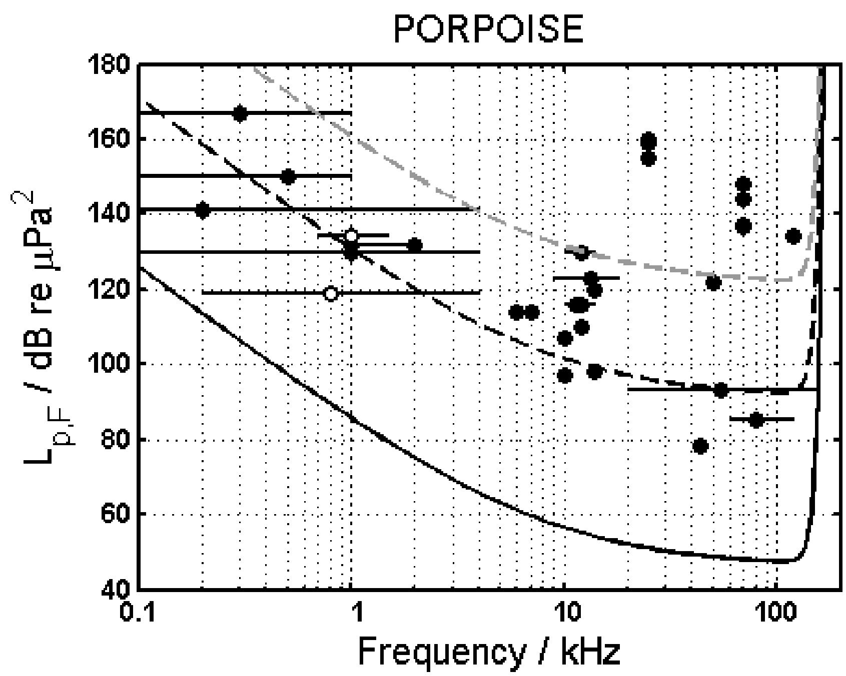

Figure 18 Threshold levels ($L_{p,F}$) of various sounds at which avoidance (or similar) behaviour has been observed in harbour porpoises (closed symbols), compared with (solid line) the NMFS composite audiogram for high frequency cetaceans (see Figure 4) and with (dashed lines) curves at 45 dB and 75 dB above the composite audiogram. Open symbols indicate levels at which no significant response was observed.

Tougaard et al. [2015] propose “an exposure limit for negative phonotaxis to be 45 dB above the hearing threshold”. Figure 18 shows that such a limit captures apart of the available data, though certainly not all.
Wensveen [2016] followed up on Tougaard’s work, including data from studies at Seamarco and concluded that “the average difference between the audiogram and a fit to the behavioural thresholds was approximately 50 dB”.

The comparison of broadband impulsive sounds (from piling, explosions and airguns) with the tonal audiogram, as in Figure 18, suggests that the frequency sensitivity of the animals hearing has an effect on the threshold levels for behavioural response, but it does not provide direct evidence that the application of frequency weighting reduces uncertainty in the impact assessment. To get such evidence, the frequency weighted broadband threshold levels above which avoidance occurs for different sound should match more closely than the unweighted levels, as demonstrated in Figure 5 for the audibility of impulsive sounds.

The current Dutch guideline [Heinis et al., 2015] is based on observed avoidance behaviour during the construction of the Borkum West I offshore wind farm [Diederichs et al., 2014] and on the [Kastelein et al., 2013] studies of behavioural reactions of harbour porpoises in captivity to playback piling sounds. They found the mean onset of a reaction in terms of jumping out of the water at an unweighted SELss of 127 dB re 1 μPa^{2}s (NMFS HF weighted SELss 88 dB re 1 μPa^{2}s, based on the difference between weighted and unweighted SELss in Table 6).
At an unweighted SELss of 145 dB re 1 μPa^{2}s (NMFS HF weighted SELss 106 dB re 1 μPa^{2}s), the number of jumps was significantly different from a baseline.
The Dutch underwater sound working group decided to establish a threshold value for avoidance at unweighted SELss exceeding 140 dB re 1 μPa^{2}s (NMFS HF weighted SELss 101 dB re 1 μPa^{2}s). That is 60 dB above the (weighted) hearing threshold for these impulsive signals (Figure 5).

Brandt et al. [2016] conclude from the analyses of the dataset of seven construction projects in German waters, that clear negative effects of piling on porpoise detections (a decline by more than 20 %) occurred at unweighted SELss exceeding 143 dB re 1 μPa^{2}s. This is a precautionary estimate. In the same study, Brandt et al. [2016] indicate that “The lowest noise level class with a decline by over 50% was found to be at 150-160 dB”. Unfortunately, the threshold levels from these field studies are not based on direct acoustic measurements, but estimated on the basis of acoustic measurements at closer distance to the pile. So the piling sound spectra to which the porpoises responded in the field are not well known. However, one may tentatively assume that the spectral content of the piling sounds at the avoidance distance in these projects was similar to the spectrum of the measurements at similar distances (15-30 km) at the Gemini wind farm. Hence the corresponding NMFS HF weighted SELss threshold level is approximately 83 dB re 1 μPa^{2}s (based on the difference between weighted and unweighted SELss in Table 6), which is about 42 dB above the (weighted) hearing threshold for these signals. The less precautionary (50 % decline) noise levels translate to NMFS HF weighted SELss levels 90-100 dB re 1 μPa^{2}s (49 to 59 dB above the hearing threshold).

Brandt et al. [2016] argue: “It is difficult to relate findings from captivity to passive acoustic monitoring studies in the field. This is because animals in captivity are constrained in their avoidance behaviour and the motivation for avoidance may differ substantially” and “Passive acoustic monitoring does not yield data on individual behaviour but on the general usage of an area by porpoises”.

The available data are summarized in Table 12.

Table 12 Weighted and unweighted SEL threshold values for porpoise behavioural response. Grey numbers were estimated, assuming the same spectral energy distribution as measured during the construction of the Gemini wind farm.

	porpoises	**unweighted SEL_{SS} in dB re 1 μPa^2s**	**NMFS HF weighted SEL_{SS} in dB re 1 μPa^2s**
BMU [2013] 'disturbance'	Free	140 dB	80 dB
Brandt et al. [2016] '20% decline'	Free	143 dB	83 dB
Brandt et al. [2016] '50% decline'	Free	150-160 dB	90-100 dB
Kastelein et al. [2013] 'onset of jumping'	Captive	127 dB	88 dB
Kastelein et al. [2013] 'jumping'	Captive	136 dB	97 dB

This suggest that an "exposure limit for negative phonotaxis" at 45 dB above the hearing threshold, which translates to a NMFS HF weighted SELss threshold level of 86 dB re 1 μPa^2s, approximates the first onset of aversive behaviour in the [Kastelein et al., 2013] as well as the observed avoidance behaviour in the field [Brandt et al., 2016].

The Brandt et al., 2016 study shows that mitigation measures affect the observed avoidance distances. However, because spectral information was not provided, these data could not be used assess whether unweighted or weighted SELss better predicted the reduction in effect distances. Also a recent publication from Dähne et al. [2017] on the effectiveness of bubble curtains in reducing habitat loss for harbour porpoises provides insufficient clear information about the reported sound levels to assess the effect of frequency weighting.

4.2 Seals

There are less data on impact of underwater sound on harbour seals and grey seals than on harbour porpoises.

4.2.1 Auditory effects

Kastak et al. [2005] measured TTS-onset in a harbour seal exposed to underwater sound (octave-band noise centred at 2.5 kHz). The unweighted SEL threshold for TTS-onset was found at 183 dB re 1 $\mu Pa^2 s$.
Kastelein et al. [2012a] measured TTS-onset in two harbour seals exposed to underwater sound (octave-band noise centred at 4 kHz). The unweighted SEL threshold for TTS-onset was found at 180 dB and 183 dB re 1 $\mu Pa^2 s$ respectively. Furthermore, both Kastak et al. [2008] and Kastelein et al. [2013b] have reported an incident in which a severe TSS (>50 dB and 44 dB threshold shift respectively) was induced in a seal, which resulted in a 7-10 dB permanent threshold shift in the first case, and recovered after 4 days in the second case.

Studies in which seals were exposed to impulsive sounds (pile driving sound playbacks [Kastelein et al., 2011] and single airgun pulses [Reichmuth et al., 2016]), did not result in measured threshold shifts. The maximum cumulative unweighted SEL in the [Kastelein et al., 2011] exposure study was 183 dB re 1 $\mu Pa^2 s$, the maximum single pulse unweighted SEL in the [Reichmuth et al., 2016] study was 180 dB re 1 $\mu Pa^2 s$. Note that [Reichmuth et al., 2016] only checked for threshold shifts at 100 Hz, so the occurrence of TTS at higher frequencies cannot be excluded. Kastelein et al. did measure 4 dB TTS (at 4 kHz) in a seal after exposure to playback piling sounds during 360 minutes (personal communication.; unpublished data). The cumulative unweighted SEL in this study would have been 193 dB re 1 $\mu Pa^2 s$ if the seal would have had its head underwater during the full duration, which was not the case. It is likely that the SELcum it received was smaller than 193 dB re 1 $\mu Pa^2 s$, because of the periods during which its head was above the water surface, but how much smaller could not be quantified.

Figure 19 shows the TTS onset threshold spectrum for phocid pinnipeds (the solid line, referred to as ‘exposure function’) as proposed in [NMFS, 2016]. The NMFS (2016) guidelines propose a phocid pinniped-weighted SELcum threshold of 170 dB re 1 $\mu Pa^2 s$ for TTS, and 185 dB re 1 $\mu Pa^2 s$ for PTS. According to Reichmuth et al. (2016), their maximum weighted SELcum with a single airgun gun pulse was approximately 156 dB re 1 $\mu Pa^2 s$, and the maximum weighted SEL in the Kastelein et al. (2011) study was 174 dB re 1 $\mu Pa^2 s$. Neither of these studies induced TTS, which appears to be consistent with the NMFS-2016 criterion for TTS onset.

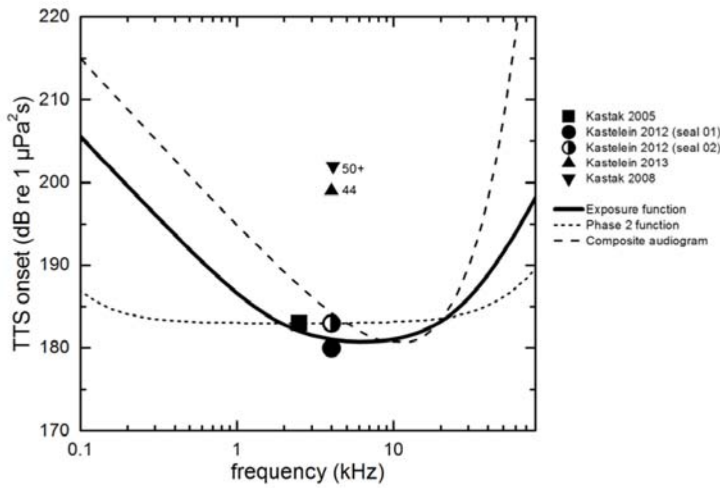

Figure 19 Phocid pinniped in water TTS exposure function, (normalized) composite audiogram, and Phase 2 exposure functions compared to high-frequency cetacean TTS data. Large symbols with no numeric values indicate onset TTS exposures. Smaller symbols represent specific amounts of TTS observed, with numeric values giving the amount of measured TTS. Fig. A20 from [NMFS, 2016].

4.2.2 *Behavioural disturbance*

There is very little information about the behavioural response of seals to underwater sounds in the literature. Some data have been published of studies for acoustic deterrents (‘seal scarers’), that are applied to protect fish farms [Jacobs & Terhune, 2002; Gordon et al., 2007; Götz & Janik, 2010; 2015; Kastelein et al., 2015e; 2017; Mikkelsen et al., 2017], for acoustic communication signals [Kastelein et al., 2006; 2006a], for pile driving sounds [Blackwell et al., 2004; Kastelein et al., 2011; Russel et al., 2016] and for airgun pulses [Harris et al., 2001; Reichmuth et al., 2016].

Figure 20 shows the threshold levels at which avoidance (or similar) behaviour is observed converted to the time-weighted $L_{p,F}$ metric and plotted as a function of the centre frequency (and bandwidth). In comparison with the similar plot for porpoises (Figure 18), the difference between the hearing threshold and the observed ‘avoidance’ thresholds seems to be larger (~60 to 70 dB rather than ~45 dB). Götz and Janik [2010] use the term ‘sensation level’ for this difference and state: “in the wild we found that seals repeatedly avoided sounds when sensation levels ranged from 59dB to 79dB (depending on sound type) with a mean value of 70dB”, but add: “It is also important to note that avoidance thresholds in captive harbour seals and harbour porpoises when no food was presented were found at sensation levels below 50dB”.

However, overall the amount of data is limited and the context in which the exposure takes place has a large influence on the reaction, so that it is hard to draw firm conclusions.

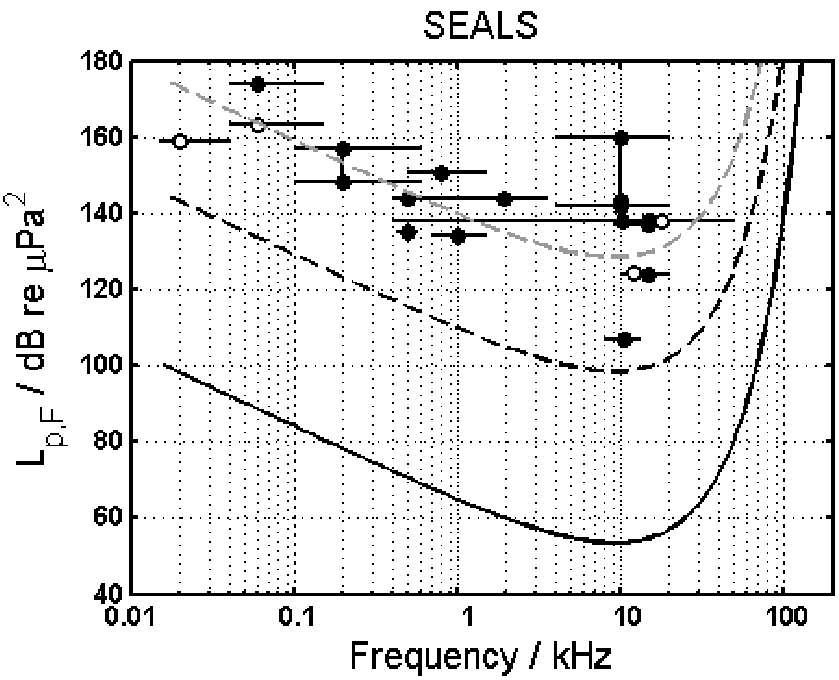

Figure 20 Threshold levels ($L_{p,F}$) of various sounds at which avoidance (or similar) behaviour has been observed in seals, compared with (solid line) the NMFS composite audiogram for phocid pinnipeds in water (see Figure 4) and with (dashed lines) curves at 45 dB and 75 dB above the composite audiogram.

The unweighted SELss threshold (142 dB) from the pile driving playback sound study [Kastelein et al., 2011] seems to be consistent with the threshold (142-151 dB) from the field observations of Russell et al. [2016]. Unfortunately, the effect of frequency weighting on these results cannot de directly obtained, because Russel et al. [2016] do not provide the spectral content of the exposure.

5 Tentative answers to the questions

5.1 Is it correct to assume that harbour porpoises are more sensitive to the underwater sounds produced by the piling for the offshore wind turbine foundations in the North Sea than harbour and grey seals?

To address this question, we consider that being more sensitive can mean different things in this context. It can refer to:
- being able to hear sound at a lower sound level
- experiencing noise induced hearing loss at a lower sound level
- experiencing behavioural disturbance at a lower sound level
- experiencing more severe fitness consequences as a result from to behavioural disturbance.

Figure 4 in this report illustrates that the hearing sensitivity of the porpoise is better than that of seals at frequencies above about 8 kHz, but that seals hear better at lower frequencies. Also note that the audiograms are measured in very quiet conditions. At sea, the corresponding detection of sounds will be most likely limited by ambient noise in a large part of the frequency range.

Note that this relative difference in hearing sensitivity cannot be directly translated to a relative difference in sensitivity to disturbance or to TTS or PTS. The difference in weighted SELcum levels required for TTS onset for porpoises (140 dB re 1 $\mu Pa^2 s$) and seals (170 dB re 1 $\mu Pa^2 s$) is of the same order as the measured differences in weighted SELss for the piling noise measured during the Gemini wind farm construction (order 25 dB to 30 dB, see Table 10). This suggests a similar risk to TTS if the both species would remain stationary at the same distance from the pile driving event. In reality however, the animal movement, diving behaviour, and potential response to the sound source will affect the accumulation of SEL.
In the current assessment scheme, a model-based approach is adopted that accounts for movement behaviour in the estimation of the risk of PTS and TTS (Heinis & de Jong, 2015). Field studies with tagged animals allow for validation of these models and more realistically estimate the risk of hearing effects. In a recent assessment of sound exposure in harbour seals during the installation of an offshore wind farm off the coast of south-east England Hastie et al. [2015] concluded that “half of the tagged seals received sound levels from pile driving that exceeded auditory damage thresholds for pinnipeds”. Note that this assessment did not yet account for the effect of frequency weighting of the SELcum.
The scarce available data on behavioural response to underwater sound suggest that porpoises are more sensitive than seals, in the sense that their avoidance threshold seems to be closer to their hearing threshold (Figure 18) than for seals (Figure 20). This was recently confirmed by Mikkelsen et al. 2017] who found that ‘simulated seal scarer sounds scare porpoises, but not seals’ (at a frequency where the hearing thresholds of both species are very similar). Since the sound levels produced by pile driving dominate at lower frequencies (< 1 kHz), the relatively high acoustic energies contribute more to the disturbing potential for seals than to porpoises. This is reflected in the predictions using frequency weighting leading to more comparable effect distances for porpoises and seals (Table 10), than if no frequency weighting is applied. This appears to be consistent with recent studies of behavioural responses showing comparable effect distances of harbour seals

responding to pile driving (Russel et al., 2016), as reported in earlier studies for harbour porpoises (Tougaard et al., 2009 & 2012; Brandt et al., 2011 & 2016; Dähne et al., 2013).

Due to a current lack of data it is beyond the scope of this review to compare the potential fitness consequences for a harbour porpoise and harbour or grey seal from the disturbance from pile driving sound.

Note that the current Dutch staged procedure for environmental impact assessments and appropriate assessments for future Dutch Offshore Wind Energy projects focuses on the effects on harbour porpoises. However, the main motivation for this focus was not the assumption that 'harbour porpoises are more sensitive to the underwater sounds produced by the piling for the offshore wind turbine foundations in the North Sea than harbour and grey seals'. It was decided to opt for the harbour porpoise because the probability of this population being impacted by the cumulative effects of impulsive sound is higher than is the case with seals. This is because, at the locations where the activities are planned, the relative population density of harbour porpoises is much higher than in the case of the two seal species, which are primarily found in coastal waters.

5.2 Is there a need to incorporate in the impact assessment the frequency spectrum of the piling sound in relation to the frequency sensitive hearing of porpoises and seals?

On the basis of a limited amount of data that supports incorporating frequency weighting in the assessment, Tougaard et al. [2015] have proposed that 'frequency weighting with a filter function approximating the inversed audiogram might be appropriate when assessing impact', and the US National Marine Fisheries Service decided that there was sufficient evidence to implement frequency weighting in its technical guidance for assessing the onset of noise induced hearing loss in marine mammals [NMFS, 2016]. Recent studies of TTS induced by airgun and playback piling sounds support the application of the NMFS HF frequency weighting functions for assessing the risk of TTS/PTS onset in harbour porpoises:

- The weighted exposure levels at TTS onset due to airgun and piling sounds are more consistent than the unweighted levels (Table 11).
- The weighted exposure spectra peak closer to the frequencies where TTS is found than the unweighted spectra (Figure 15)

In this study, we have also demonstrated (Figure 5) that frequency weighting can explain the differences in audibility of different impulsive sounds. Hence, it is tempting to assume that the same holds for behavioural response. The limited available data suggest that a frequency weighted threshold level at about 45 dB above the hearing threshold, provides a rough approximation for the first onset of aversive behaviour in porpoises. For seals this threshold seems to be about 60 to 70 dB above the hearing threshold, but there are few data points to support this hypothesis. However, there is too little useful data to draw final conclusions about the need to incorporate auditory frequency weighting in the impact assessment.

5.3 What are the consequences of frequency weighting for the threshold values for hearing loss and behavioural response?

Incorporating frequency weighting in the exposure assessment automatically means that appropriate weighted threshold levels for hearing loss and behavioural response would need to be established. At this moment there is not sufficient information available to establish such thresholds for behavioural response.

Recent studies of TTS induced by airgun and playback piling sounds [Kastelein et al., 2017a] support the application of the NMFS (2016) HF frequency weighting functions and threshold values for assessing the risk of TTS/PTS onset in harbour porpoises. NMFS (2016) also suggests thresholds for TTS/PTS onset in harbour seals, but these are based on very little data.

Data and modelling of underwater sound from piling for the Gemini wind farm in the North Sea was originally done using unweighted SELss. It is likely that an updated assessment on the basis of frequency-weighted levels would lead to a different prediction of the avoidance zone for porpoises than an assessment on the basis of unweighted sound exposure levels. At this moment there is insufficient information to establish frequency weighted threshold values. Research into frequency dependence is urgently needed to enable development and international harmonization of frequency weighted thresholds for behavioural response.

Mitigating measures such as noise mitigation screens, bubble screens and alternative piling techniques (e.g. ‘ Blue Piling’) are more effective in reducing weighted sound exposure levels than in reducing unweighted levels, because most of these techniques are more effective at the higher frequencies (well above 100 Hz) of the piling sound [Bellman, 2014]. Dähne et al [2017] concluded from passive acoustic monitoring during the construction of the DanTysk offshore wind farm that the reduction of high-frequency sound by bubble curtains effectively mitigated temporary habitat loss and risk of hearing loss for harbour porpoises. They suggest that regulation should be based on frequency-weighted sound levels.

5.4 Are the available acoustic models sufficiently accurate to incorporate the frequency weighting in the impact assessment? If not, how can uncertainty be reduced?

The accuracy requirements for the acoustic models have not yet been established and need further discussion.

The current models are in the frequency domain and are able to take into account the frequency dependence of the acoustic propagation as well as frequency weighting functions for the mammal response.

For porpoise related studies, the uncertainty is mainly in the high frequency part of the spectrum, where it is probably more important to describe the ‘line source’ properties of the pile and where the modelling of the effect of wind on the sound propagation needs further improvement. The high frequency modelling also has its limitations in terms of requirements for computer memory and cpu-time, and in the level of detail of the modelling of pile and hammer force.

For assessment of the effects on seals, also the lower frequencies are relevant, where there are still uncertainties in the modelling of the effect of the sediment on the sound propagation.

The models would need further development to take into account the frequency dependence of mitigating measures such as noise mitigation screens, bubble screens and alternative piling techniques (e.g. ‘ Blue Piling’).

6 Knowledge gaps and research proposals

It is currently not possible to draw firm conclusions about the effects of (impulsive) underwater sound on porpoises and seals and the appropriate metrics to quantify these, due to limited amount of available data. Hence, it is advised to initiate studies to fill this data gap. Some suggestions for further studies are given below.

6.1 Analysis of data from field studies during the construction of the Luchterduinen and Gemini wind farms

The underwater sound from the piling for the Luchterduinen and Gemini wind farms has been monitored at four measurement distances (ranging from 750 m to 65 km) for a small number of piles. ITAP has reported the measurement results and the data are available at TNO.

WMR has collected data of C-POD observations of porpoise clicks during the piling for Gemini and data of behaviour of tagged seals during the piling for both wind farms. Initial analysis of the data has been carried out, but further correlation with the acoustical data might provide more information about the dose-effect relationships.

6.2 Further analysis of data from German field studies

The studies of Brandt et al. [2016] and Dähne et al. [2017] provide valuable information about behavioural responses of harbour porpoises during the construction of offshore wind farms in German waters. However, these publications provide insufficient information on the acoustic exposure to quantify the dose-effect relationship in terms of weighted and unweighted metrics. We propose to contact the authors of these studies and to investigate possibilities for collaborative research aimed at obtaining quantitative information of the relationship between observed behavioural response and weighted and unweighted acoustic exposure metrics.

6.3 Studies of porpoise behavioural response to sound pulses with different frequency content

Seamarco could carry out tests of the behavioural response of a harbour porpoise to impulsive sounds with different frequency content, to investigate whether this response is correlated with frequency-weighted or with unweighted exposure metrics. The exposure to impulsive sounds with different frequency content could be achieved via playback of artificially modified sounds. An alternative option would be to use the frequency filtering that is produced by the bubble-wrap screen that is installed to acoustically separate the indoor and outdoor pools during airgun tests at Seamarco. This screen more effective at high frequencies. An option could be to compare the response of the porpoise to low level airgun exposure tests without the bubble-wrap screen with the response to exposures at the same (weighted and/or unweighted) exposure level with the bubble-wrap screen.

6.4 Studies of the effects of masking sound on behavioural response to pilng sounds

The analysis of the effects of frequency weighting on measured piling noise (Figure 9) indicates that particularly the porpoise weighting reduces the ratio of the piling noise levels to the background noise. Masking of the exposure stimuli by background noise can affect the behavioural response [Kastelein et al. 2011]. Seamarco could carry out play back studies to test the effect of masking on the behavioural response of a harbour porpoise to impulsive sounds.

TNO could also further investigate the potential for masking of piling sounds by background noise at the North Sea, based on available measurement data and the approach suggested by Erbe et al. [2015] and von Benda-Beckmann et al. [2015].

7 Signature

The Hague, November 2018

TNO

Coen Ort
Head of department

Christ de Jong
Author

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