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Evaluating the predictive strength of underwater noise exposure criteria for marine mammals[a]

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ABSTRACT:
The aim of underwater noise exposure criteria in a regulatory context is to identify at what received levels noise-induced effects are predicted to occur, so that those effects may be appropriately considered in an evaluation or mitigation context under the respective regulatory regime. Special emphasis has been given to hearing related impairment of marine mammals due to their high sensitivity to and reliance on underwater sound. Existing regulations of underwater noise show substantial qualitative and quantitative discrepancies. A dataset acquired during an experiment that induced temporary threshold shift (TTS) in a harbor porpoise (*Phocoena phocoena*) from Lucke, Siebert, Lepper, and Blanchet [(2009). J. Acoust. Soc. Am. **125**, 4060–4070] was reanalyzed to see if various exposure criteria predicted TTS differently for high-frequency cetaceans. This provided an unambiguous quantitative comparison of predicted TTS levels for the existing noise exposure criteria used by regulatory bodies in several countries. The comparative evaluation of the existing noise exposure criteria shows substantial disagreement in the predicted levels for onset for auditory effects. While frequency-weighting functions evolved to provide a better representation of sensitivity to noise exposure when compared to measured results at the criteria's onset, thresholds remain the most important parameter determining a match between criteria and measured results.
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I. INTRODUCTION

Over the past decades, various countries' governmental regulatory agencies have developed or adopted noise exposure criteria to assess or, depending on the regulatory approach, reduce the risk of physiological effects from exposure to intense underwater noise on the auditory system of marine fauna. Special emphasis has been given to marine mammals, due to their high sensitivity to and reliance on underwater sound. In developing these criteria, marine mammal research (and regulation) followed the rationale and methods used for developing similar criteria for protecting humans from occupational exposure to injurious noise levels (e.g., OSHA, 2013). The integral parts of these criteria are the thresholds for the onset of temporary and permanent threshold shift (TTS and PTS, respectively) and the auditory weighting functions, which reflect differences in a species' hearing sensitivity over their frequency range of hearing. By measuring the relevant auditory parameters in marine mammal species held in human care, it was possible to derive robust quantitative information, which allowed scientists to determine criteria for most marine mammal species. Adopting practices similar to those for humans, dual criteria based on the peak sound pressure level (Lpk) and weighted sound exposure level (SEL) have been developed.[1] The pertinent scientific knowledge has evolved over the past decades; several landmark scientific publications provided the basis for developing an increasingly advanced approach for deriving noise exposure criteria for marine mammals.

There is no internationally harmonized set of underwater noise criteria. Indeed, discrepancies between legal systems in different countries have resulted in different "philosophies" for the approaches used to establish marine mammal noise regulations. The situation is further complicated by the fact that noise exposure regulations in various countries are subject to different cycles of review and updating. This has resulted in an assortment of noise exposure criteria that share some underlying principles yet differ in their complexity and scientific rigor. Here, the marine mammal noise exposure criteria developed in the USA (as the most commonly used/referenced set of criteria) are evaluated by comparing their predictions of TTS onset with those from criteria used in Germany and New Zealand. Stöber and Thomsen (2019) compared different noise exposure criteria based on modelled impact ranges for a simplified pile driving scenario. In the present study, raw data acquired in a TTS study (Lucke *et al.*, 2009) that directly led to the noise exposure thresholds for impulsive sources in the US National Marine Fisheries Service (NMFS, 2018) were

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reanalyzed to determine if the various noise exposure criteria being considered would predict TTS onset consistent with those measured. The dataset provides a reference that enables quantitative comparison of criteria proposed over the past decade. The results can be used to inform recommendations on the practical use of exposure criteria.

II. NOISE EXPOSURE CRITERIA FOR MARINE MAMMALS

Criteria for exposure of marine mammals to underwater noise developed under three different regulatory regimes are compared in this study. The Marine Mammal Protection Act (Congress of the United States of America, 2019) is the most relevant legal framework in the USA with regard to effects on marine mammals. It discerns between Level A harassment (injurious effects, such as PTS) and level B harassment (such as behavioral disturbance or TTS). In 1995, the NMFS set a threshold for Level A harassment from impulsive noise at a received sound pressure level (SPL) at 90 of 180 dB re 1 μPa for mysticetes (baleen whales), sperm whales (*Physeter macrocephalus*), and *Kogia spp*., and 190 dB re 1 μPa for pinnipeds and most odontocetes (toothed whales); the received SPL90 threshold for Level B harassment from impulsive noise was set to 160 dB re 1 μPa, where SPL90 is the threshold evaluated using a 90% energy signal duration. (No frequency band is specified for these onset values.) In the absence of empirical scientific information on onset levels for TTS and PTS in marine mammals, these values were considered precautionary (Southall *et al*., 2007). These harassment thresholds were applied to individual noise pulses or instantaneous sound levels; they do not consider the overall duration of the noise or its acoustic frequency distribution.

Criteria that do not account for exposure duration or noise spectra are generally insufficient on their own for assessing hearing injury. Human workplace noise assessment metrics consider sound level as well as the duration of exposure and sound spectral characteristics. For example, the International Institute of Noise Control Engineering and the Occupational Safety and Health Administration (OSHA) suggests noise exposure thresholds for humans in C-weighted peak sound level and A-weighted time-average sound level (dB $L_{\mathrm{eq,A}}$) (OSHA, 2013). They also suggest exchange rates that increase the allowable thresholds for each halving or doubling of exposure time. This concept is known as Equal Energy Hypothesis (EEH) and assumes that sounds of equal cumulative sound energy results in an equal risk for threshold shift (Finneran, 2015). This approach presumes that hearing damage depends on the spectral sensitivity weighted sound level perceived by the human ear.

An expert panel convened in 2002 by the US National Oceanic and Atmospheric Administration (NOAA)'s Ocean Acoustics Program reviewed literature on marine mammal hearing and noise-induced effects and proposed new noise exposure criteria based on assessment methods similar to those applied for humans (Southall *et al*., 2007). The resulting recommendations introduced dual acoustic injury criteria for impulsive sounds that included Lpk thresholds and $\mathrm{SEL}_{24\mathrm{h}}$ thresholds, where the subscripted "24 h" refers to the accumulation period for calculating SEL of 24 hours. The Lpk criterion is not frequency weighted, whereas $\mathrm{SEL}_{24\mathrm{h}}$ is frequency weighted according to one of four marine mammal species hearing groups: low-, mid- and high-frequency cetaceans (LF, MF, and HF cetaceans, respectively) and pinnipeds in water ($\mathrm{P_{ws}}$). These weighting functions are referred to as frequency-weighting filters (and are applied in a similar way as the A-weighting filter for humans). $\mathrm{SEL}_{24\mathrm{h}}$ thresholds were obtained by extrapolating measurements of onset levels of TTS in belugas by the amount of TTS required to produce PTS in chinchillas. The Southall *et al.* (2007) recommendations do not specify an exchange rate that would account for recovery over time, meaning that the thresholds remain the same regardless of the exposure duration (in other words, it infers a 3 dB exchange rate, whereby a doubling of the exposure time to a constant signal exactly doubles the sound level for the purpose of the criteria).

An increasing body of auditory information (including TTS data) for marine mammals allowed revising the classification of species into functional hearing groups and tailoring of the weighting functions for each group (Finneran and Jenkins, 2012; NMFS, 2018). This changed the shape of the weighting functions and, accordingly, influenced the resulting attenuation of specific frequency ranges.

In 2012, the US Navy published a new set of criteria for assessing Navy operations (Finneran and Jenkins, 2012). Their analysis incorporated new equal-loudness contours for dolphins to update weighting functions and injury thresholds for LF, MF, and HF cetaceans. These criteria would later be revised (Finneran, 2016), where the author differentiated between six functional marine mammal hearing groups and proposed new or updated weighting functions for these groups.

In 2013, NOAA published an initial draft guidance, not intended as a formal regulatory basis, for assessing the effects of anthropogenic sound on marine mammals (NOAA, 2013). While the weighting functions proposed in the draft guidance were based on the work by Finneran and Jenkins (2012), the definitive and formally approved technical guidance (NMFS, 2018) reflects the revised weighting functions developed by Finneran (2016).[2]

In German waters, regulation of underwater noise exposure is tailored specifically to reduce or mitigate the effects of the construction of offshore wind turbines on harbor porpoises (*Phocoena phocoena*) as a key indicator species [Bundesministerium für Umwelt (BMU), 2013]. Lucke *et al.* (2009) tested the effect of a single air gun on a male harbor porpoise. They measured TTS at 4 kHz and found that > 6 dB of TTS was induced at a received (unweighted) SEL90 of 164.3 dB re 1 $\mu\mathrm{Pa}^2\cdot\mathrm{s}$, where SEL90 is the 90% energy SEL, corresponding to an unweighted per-strike SEL of 164.8 dB re 1 $\mu\mathrm{Pa}^2\cdot\mathrm{s}$. The main energy of the fatiguing stimulus (air gun pulse) was centered below 500 Hz, but a substantial amount of energy was also present at higher frequencies. This was the first TTS study on harbor porpoises, and it provided relevant data for defining the noise exposure criterion for HF cetaceans. The German regulation of (impulsive) underwater noise (BMU, 2013) is directly based on the results of that study, and other countries also considered these results as part of their regulations. Under these regulations, sound levels 750 m from the source (pile driving operation) must not exceed a per-strike unweighted SEL of 160 dB re 1 μPa^2·s or peak-to-peak sound pressure level (Lucke *et al.*, 2009) of 190 dB re 1 μPa.

In New Zealand the process of revising the *Code of Conduct for Minimising Acoustic Disturbance to Marine Mammals from Seismic Survey* is still ongoing, but an unofficial draft was released under New Zealand's Official Information Act in 2017 [New Zealand Department of Conservation (NZDOC), 2017]. This code is specifically tailored to prevent auditory injury to Māui dolphin (*Cephalorhynchus hectori maui*) as the species of greatest conservation concern in New Zealand. In this code, a single −20 dB step is applied as a weighting function below 1 kHz. A PTS weighted sound exposure threshold of 153 dB re 1 μPa^2·s is recommended as part of NZDOC's code (2017). Noise exposure levels are defined for impulsive and non-impulsive sounds, and cumulative exposure is accounted for, albeit on a different time scale (10 s) than the NMFS criteria (24 h).

While regulations of underwater noise have also been developed by other countries, the comparative evaluation in the present study was restricted to six acoustic criteria discussed above that either are in current use or have been widely considered, namely Southall *et al.* (2007), Finneran and Jenkins (2012), Finneran (2016), NZDOC (2017), and BMU (2013). The relevant criteria thresholds and related notes are summarized in Table I. It bears noting that there is no general agreement among regulators on the severity of impact associated with auditory threshold shift; in the USA regulatory framework, the threshold level for injury is defined as the onset of PTS, while other jurisdictions place that threshold level at the onset of TTS.

III. METHODS

A. Data analysis

A total of 24 air gun pulses from a 20 in^3 (0.33 L) air gun were recorded during the 2007 experiments (Lucke *et al.*, 2009) in Kerteminde Harbour, Denmark. Of those 24 pulses, 19 were recorded with the same hydrophone (Reson 4014B) and at a common sampling rate (320 kHz); this standardized subset was analyzed in this study. The five excluded pulses were emitted at ranges of 80 m or farther from the subject, and they did not induce TTS in the harbor porpoise (*Phocoena phocoena*) tested in that experiment. Each pulse was extracted from the original recordings and analyzed using calibration information and other sound level computation details reported in Lucke *et al.* (2009).

The signal sample shown in Fig. 1 reveals a strong harmonic signature (50 Hz and overtones) caused by the power

TABLE I. List of noise exposure criteria (onset of TTS) for impulsive sounds considered in the comparative analysis. LF = Low-frequency cetacean, MF = Mid-frequency cetacean, HF = High-frequency cetacean. A dash denotes no threshold value given; n/a indicates not applicable.

		Single impulse threshold L_E (dB)		Multiple impulse threshold L_E (dB)				
Noise exposure criterion	Functional hearing group	TTS	PTS	TTS	PTS	Weighting	Stimulus	Comments
Southall *et al.* (2007)	LF	183	198	183	198	M-weighting $L_{E,\mathrm{M,\ LF}}$	Seismic watergun[a]	Single impulse SEL
	MF	183	198	183	198	M-weighting $L_{E,\mathrm{M,MF}}$	Seismic watergun[a]	
	HF	183	198	183	198	M-weighting $L_{E,\mathrm{M,HF}}$	Seismic watergun[a]	
Finneran and Jenkins (2012)	LF	—	—	172	187	$L_{E,\mathrm{LF,24h}}$	Impulsive	Cumulative SEL
	MF	—	—	172	187	$L_{E,\mathrm{MF,24h}}$	Impulsive	
	HF	—	—	146	161	$L_{E,\mathrm{HF,24h}}$	Impulsive	
Finneran (2016)	LF	—	—	168	183	$L_{E,\mathrm{LF,24h}}$	Impulsive	Cumulative SEL
	MF	—	—	170	185	$L_{E,\mathrm{MF,24h}}$	Impulsive	
	HF	—	—	140	155	$L_{E,\mathrm{HF,24h}}$	Impulsive	
New Zealand Dept. of Conservation (2017)	Unspecific[b]	—	153[c]	—	153[c]	$L_{E,\mathrm{DC(NZC)}}$[d]	Impulsive	A total New Zealand Code-weighted (with −20 dB applied to energy at frequencies below 1 kHz) sound exposure level received from one pulse (SEL$_{\mathrm{DC(NZC)}}$) as determined by total length of duty cycle
BMU (2013)	HF	160	—	—	—	n/a	Single impulse (specific for pile driving)	Based on Lucke *et al.* (2009); not (ac-)cumulative

[a] Based on Finneran *et al.* (2002).

[b] Species of greatest conservation concern is the Māui dolphin.

[c] DOC recognizes that the definition of PTS as used in the USA "was precautionary and likely provides an underestimate." Based on this statement, the NZDOC criterion is categorized under PTS.

[d] Duty cycle sound exposure level, measured over a period of time determined by the total length of the duty cycle (NZDOC, 2017).

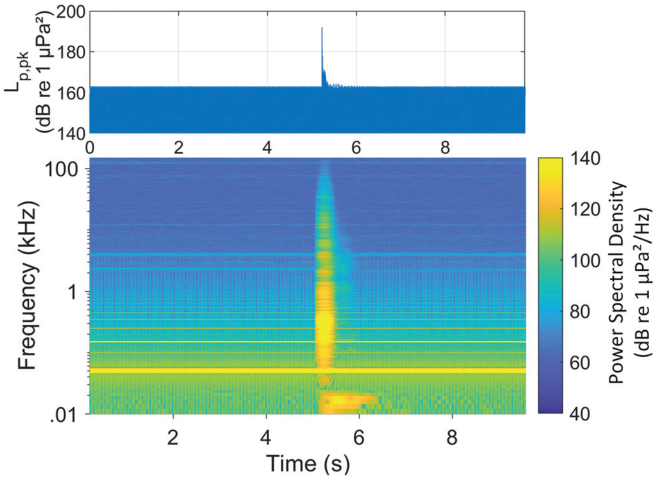

FIG. 1. Example of time-series of peak sound pressure level (top) and spectrogram (bottom) for the pulse recorded on 28 May 2007. Data used are the original recordings from Lucke *et al.* (2009).

supply of the recording system. The use of a 50 Hz notch filter for removing this spurious energy was evaluated. We found that removing the 50 Hz signal component reduced the broadband sound exposure level by no more than 0.1 dB; the filter, however, changed the peak sound pressure levels by ±0.75 dB. Given that the 50 Hz signal did not affect appreciably the SEL, which is the primary metric for this analysis, the filter was not applied, and the signal processing was kept consistent with Lucke *et al.* (2009).

B. Frequency weighting

Southall *et al.* (2007), Finneran and Jenkins (2012), and Finneran (2016) include auditory frequency weighting functions that are applied to the sounds before they are summed to find the daily SEL. These functions account for the fact that the potential for anthropogenic sounds to impact marine mammals is largely dependent on whether the sound occurs at frequencies that an animal can hear (unless the sound pressure level is so high that it can cause physical tissue damage regardless of frequency). The four sets of auditory weighting functions for cetaceans are compared in Fig. 2. The logarithmic auditory weighting functions are band-pass filters that are parameterized according to the formula:

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

where C is a constant used to normalize the function to 0 dB at its maximum value, f_1 defines the lower limit of the filter, f_2 defines the upper limit of the filter, and a and b are

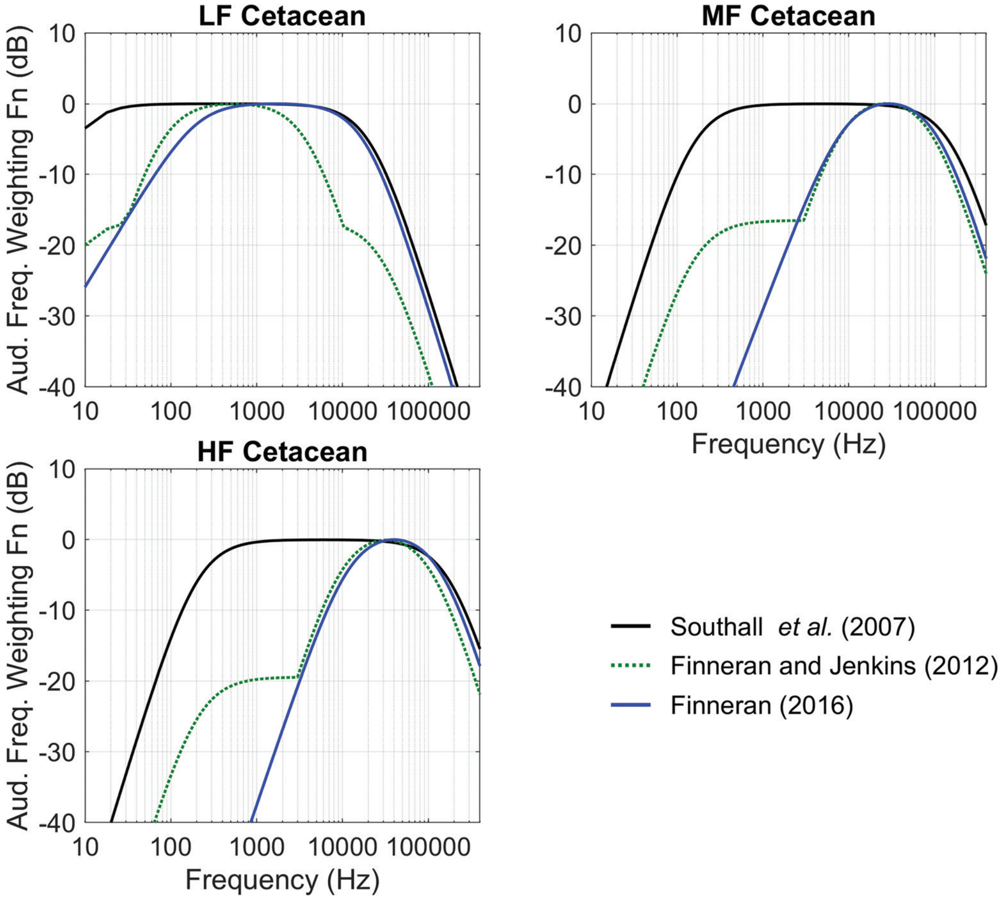

FIG. 2. The evolution of auditory frequency weighting functions for functional marine mammal hearing groups from Southall *et al.* (2007), Finneran and Jenkins (2012), and Finneran (2016).

parameters that affect the rate at which the filter rolls off below and above the limit frequencies. The logarithmicuditory weighting function, $W(f)$, is related to the auditory frequency weighting function $w_{\text{aud}}(f)$ according to (Heaney *et al.*, 2020):

$$W(f) = 10\log_{10} w_{\text{aud}}(f)\, dB,$$

and exact form of the functions and the parameters are contained in the references. The application of the weighting functions to sampled data are described in Tougaard and Beedholm (2019) and Martin *et al.* (2020).

The simple weighting function considered by the NZDOC (2017) reduces by 20 dB all one-third octave (base 10) bands with nominal center frequencies of 800 Hz and below, leaving the 1 kHz and above one-third octave (base 10) bands unweighted. For this analysis the NZDOC (2017) weighting function was implemented as a finite-impulse-response filter as described in Martin *et al.* (2020).

Lucke *et al.* (2009) measured TTS in a harbor porpoise exposed to single air gun impulses in shallow water. The main aim of the current study is to compare existing noise exposure criteria by using these original recordings as a reference dataset. The primary metric chosen for comparing criteria is the SEL.

After applying each criterion's weighting function to the recorded signals that elicited TTS in the reference study, ideally, the resulting received SELs should provide the same 'verdict' with regard to TTS. It should be noted that the number of events where received SELs exceeded the TTS threshold is higher (5) than the number of noise exposures considered by Lucke *et al.* (2009) for determining the TTS threshold (3); this is a result of testing the animal's hearing sensitivity not only at 4 kHz (where TTS was documented after three separate exposures) but also at higher frequencies without resulting in TTS at those frequencies (see, e.g., Fig. 11 in Lucke *et al.*, 2009). While the additional two cases of SEL exceeding the TTS threshold did not contribute to its determination, these fully documented data points allow for a larger sample size for comparing the predictive ability of the noise exposure criteria in the present study.

IV. RESULTS

The SELs of a given exposure session where TTS was elicited in the reference study, after applying the weighting function, should exceed the threshold level predicting TTS under each criterion. Table II shows the results for all sets of noise exposure criteria considered, with typographical highlights denoting individual criteria exceedances in relation to experimentally observed TTS thresholds as explained in the caption.

The M-weighted SEL values did not exceed the TTS criterion for HF cetaceans proposed by Southall *et al.* (2007) for any of the exposures exceeding the onset level for TTS reported by Lucke *et al.* (2009). Applying the criterion determined by Finneran and Jenkins (2012), however, results in three events of threshold exceedance, those proposed by Finneran (2016) in four, the NZDOC (2017) criteria in five, and BMU (2013) in seven events. The margins by which the weighted SELs differed from the respective thresholds in these events range from 0.9 dB (Finneran and Jenkins, 2012) to 19 dB (Southall *et al.*, 2007), while the SEL values that resulted in TTS in the original experiments exceeded the TTS threshold (which was derived from three of those values) by 1.7 to 2.3 dB.

V. DISCUSSION AND CONCLUSIONS

This evaluation is a systematic review of differences between existing criteria for protecting marine mammals from injurious levels of anthropogenic noise. It aims at providing a scientifically robust baseline for regulatory decision-making in adopting mitigation thresholds by enabling an informed reflection on the current regulation of underwater noise and assisting in the potential identification of alternatives. This study does not proffer an opinion on which criteria are more appropriate for regulating underwater noise effects on marine mammals, nor does it imply a judgement on their validity for use by different jurisdictions or regulatory approaches.

The analyses are based on a reference dataset recorded during a TTS experiment with a harbor porpoise, a HF cetacean, exposed to acoustic stimuli from a seismic source (Lucke *et al.*, 2009). By recomputing the relevant exposure metrics of the nineteen single air gun impulses used in that study in accordance with individual weighting functions, the most relevant noise exposure criteria were compared in terms of their predicted onset levels for auditory impairment. The results from the SEL analyses provide a comparison between the directly measured SEL that caused a threshold shift in a harbor porpoise and the criteria for HF cetaceans contained in various regulatory guidelines or unsanctioned directives. The differences in effect levels evidenced by this evaluation can be used as a starting point to consider possible offsets to current regulatory guidelines. It must be noted, however, that the outcome is based on a single experimental evidence and natural variability in susceptibility to TTS should be expected.

The received levels determined for various criterion-specific exposure metrics shows that applying the NZDOC (2017) criterion provides results that are in complete agreement with the results by Lucke *et al.* (2009). Building on the results by Lucke *et al.* (2009) to inform the HF thresholds, the criteria proposed by Finneran (2016) and implemented in NMFS (2018) miss one instance of TTS by a margin of 2 dB, while those in Finneran and Jenkins (2012) miss two instances but only by 0.8 dB and 1.4 dB, respectively.

The BMU (2013) criterion yields two false positive results, indicating that it is systematically overestimating the potential for inducing TTS in HF cetaceans. This would rank the criterion as the most precautionary, in line with the findings of Stöber and Thomsen (2019). The outcome, however, must be viewed in the light of the fact that the BMU criterion originates directly from the results of Lucke *et al.*

TABLE II. Reanalysis of the nineteen single air gun impulses used in Lucke *et al.* (2009) to determine the received levels at the test subject for various criterion-specific exposure metrics. Shaded rows denote the trials where the SEL for onset of TTS as determined by Lucke *et al.* (2009) was exceeded. Entries that exceed the TTS threshold for different criteria (shown in the column headers) are highlighted in bold italic.

				Criterion-specific SEL, (dB re 1 μPa$^2\times$s)				
					HF-weighted			
Date	Session	Peak-to-Peak (dB re 1 μPa)	SPL90 (dB re 1 μPa)	None BMU (2013)	Southall *et al.* (2007)	Finneran and Jenkins (2012)	Finneran (2016)	NZDOC (2017)
TTS threshold				160	183	146	140	153
16 Feb 2007	aft1	182.7	163.4	150.4	147.0	128.2	119.0	136.7
18 Feb 2007	aft1	188.2	169.6	155.5	152.2	133.8	126.2	141.2
19 Feb 2007	morn1	187.8	170.0	155.8	152.5	134.0	126.5	141.0
19 Feb 2007	aft1	173.9	158.4	144.6	141.5	122.6	112.2	133.1
06 Mar 2007	mid1	176.5	160.6	146.6	143.4	124.1	109.6	132.7
07 Mar 2007	aft1	186.2	166.8	153.7	150.4	131.7	123.3	139.8
08 Mar 2007	morn1	196.1	183.3	***161.9***	159.5	141.0	133.6	149.5
08 Mar 2007	aft1	192.0	172.3	157.6	154.4	135.7	126.8	144.7
09 Mar 2007	aft1	192.7	174.2	157.9	155.1	136.2	126.5	146.3
11 Mar 2007	morn1	189.4	169.8	156.3	153.4	134.2	121.6	143.8
11 Mar 2007	aft1	188.1	169.3	156.2	152.4	133.8	125.5	142.3
02 Apr 2007	morn1	198.9	186.1	***165.1***	162.8	144.6	138.0	***153.2***
30 Apr 2007	aft1	192.6	170.9	156.8	154.0	136.0	130.4	145.7
01 May 2007	morn1	195.1	177.1	159.1	156.9	139.0	133.1	148.8
23 May 2007	morn1	200.2	184.7	***164.6***	162.3	145.2	***141.1***	***154.7***
24 May 2007	morn1	196.4	179.7	***161.1***	158.4	141.8	137.8	149.2
26 May 2007	morn1	202.1	186.2	***165.7***	164.0	***148.1***	***145.1***	***157.0***
28 May 2007	morn1	201.9	184.1	***165.9***	163.9	***146.9***	***142.8***	***157.8***
29 May 2007	mid1	202.3	186.4	***167.3***	165.8	***149.1***	***145.6***	***157.3***

(2009), and the overestimation is due to a safety margin of 4 dB added by the regulator to account for the potentially aggravating effect of multiple exposure as well as natural variability in susceptibility to TTS. The criterion does not apply frequency weighting, which means it does not generalise easily to other scenarios and species groups as it is does not take into account the relative sensitivity of different hearing groups to the frequency content of the source.

The frequency weighting functions applied in the noise exposure criteria from the NMFS technical guidance and its precursor studies as well as the one discussed by NZDOC (2017) discount the low-frequency energy contained in the seismic air gun impulses. The NZDOC (2017) criterion, however, applies only a single weighting step and not auditory weighting functions as in the NMFS criteria. Similar to the BMU criterion, it is likely to lack adaptability to animal groups other than HF cetaceans. Over the past decades, these functions evolved to provide what is arguably a more realistic representation of the animals' frequency-related sensitivity (or functional hearing groups' sensitivity—for this purpose) to noise exposure. However, in comparison to measured results from a single HF-cetacean, the onset threshold itself remains the most important parameter determining a match between criteria and experimental outcome.

It is important to note that applying the weighting functions results in criterion-specific SEL, (i.e., from a scientific perspective) the levels are not representing the same metric (Tougaard *et al.*, 2015). This fact is often overlooked in a regulatory context. Another aspect to consider is that the existing noise exposure criteria differ in regard to the number of impulses and integration time: while the NMFS criteria in the USA consider the acoustic energy released by an activity (such as pile driving or seismic surveying) over a 24-h period limit, the German criterion (BMU 2013), for example, is based on a single impulse.

In summary, comparing existing noise exposure criteria shows substantial differences in their capability to predict auditory effects such as TTS, at least for HF cetaceans. While the most recent underwater noise criteria are based on the best available science, there is still an overarching paucity of relevant auditory data to inform the definition of the underwater noise exposure criteria for all marine mammal species.

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[1] The standard ISO 18405 Underwater Acoustics–Terminology (ISO, 2017) provides an updated lexicon of metrics and terms (previous standards: IEC, 1994; ANSI, 2013) that is followed here. According to the ISO standard, cumulative sound exposure level will be abbreviated as SEL (with additional qualifiers as needed), except in tables and equations where the symbol L_E (with additional qualifiers) will be used.

[2] An interim draft guidance released by NOAA in 2015 is not considered in this study because its high-frequency criterion is identical to the one in the definitive 2018 release and thus would not rank differently in the analysis.

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