From: Tania Davey
To: Hornsea Project Three
Subject: TWT response to Examiner"s questions: supporting information 1
Date: 14 January 2019 21:22:48
Attachments: Defra revised approach policy (ref1).pdf
NOAA guidance 2016 (ref 4).pdf
Southall et al 2007 marine mammal noise exposure criteria (ref 3).pdf

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Dear Sir/Madam

Following my email regarding The Wildlife Trusts response to the Examiner's questions, please find attached the following papers referenced in our response:

- Reference 1: Defra Policy to ensure that all existing and potential commercial fishing operations are managed in line with Article 6 of the Habitats Directive
- Reference 3: Southall, BL, Bowles, AE, Ellison, WT, Finneran, JJ, Gentrym RL, Greene, CR, Kastak, D, Ketten, DR, Miller, JH, Nachtigall, PE, Richardson, WJ, Thomas, JA and Tyack, PL, 2007. Marine Mammal Noise Exposure Criteria: Initial Scientific Recommendations. Aquatic Mammals, Volume 33, Number 4, 2007.
- Reference 4: National Marine Fisheries Service, 2016 (NOAA). Technical Guidance for Assessing the Effects of Anthropogenic Sound on Marine Mammal Hearing: Underwater Acoustic Thresholds for Onset of Permanent and Temporary Threshold Shifts.

Due to the size of the attachments, I will send a further email with the final 3 attachments.

Kind regards

Tania

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REVISED APPROACH TO THE MANAGEMENT OF COMMERCIAL FISHERIES IN EUROPEAN MARINE SITES - OVERARCHING POLICY AND DELIVERY DOCUMENT

Purpose

1. This paper outlines the Department's overarching policy approach and key implementation steps to ensure that all existing and potential commercial fishing operations are managed in accordance with Article 6 of the Habitats Directive.

2. The revised approach applies to all European Marine Sites (EMS) and potential Special Protection Areas (pSPAs) and possible Special Areas of Conservation (pSACs)[1] in England. It aims to ensure that, in order to comply with Article 6 of the Habitats Directive, management measures are identified for high risk features by December 2013, and any additional fishery management measures for the conservation of the abovementioned sites are in place by 2016. The approach for the conservation of EMSs in the offshore marine area is outlined in paragraph 13.

Context

3. Government and Fishery Regulators in England (primarily the Marine Management Organisation (MMO) and Inshore Fisheries and Conservation Authorities (IFCAs))[2] have legal obligations to ensure that fishing activities (including existing fishing activities), which could adversely affect EMSs are managed in a manner that secures compliance with the requirements of Article 6 of the EU Habitats Directive. Conservation of these sites contributes to the delivery of Defra's aim to conserve and enhance the marine environment and promote sustainable fisheries.

4. In order to ensure that EMSs receive the requisite level of protection, and ensure compliance with the EU Birds and Habitats Directives, Government has decided to revise the approach to the management of commercial fisheries affecting EMS. Building on existing management measures, this will ensure that all existing and potential commercial fishing activities are subject to an assessment of their impact on EMSs.

5. It is the expectation of the Department that appropriate management measures will need to be regulatory in nature to ensure adequate protection is achieved. Management decisions should be based on the best available evidence, but using a precautionary approach. Reflecting European Commission guidance[3] on the management of fisheries in European Marine Sites, "*the proposed measures should be consistent with the conservation objectives for the sites concerned"* and we expect Regulators to take a precautionary approach, "*according to which the absence of adequate scientific information should not be used as a reason for postponing or failing to take management measures"*.

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[1] pSPAs and pSACs are sites on which Government has initiated public consultation on the scientific case for designation as a Special Protection Area or candidate Special Area of Conservation. For ease of reference EMS, pSPAs and pSACs are referred to collectively as "EMSs".

[2] There could also be other relevant regulators or competent authorities with responsibility for a particular site.

[3] FISHERIES MEASURES FOR MARINE NATURA 2000 SITES
http://ec.europa.eu/environment/nature/natura2000/marine/docs/fish_measures.pdf

Delivery

6. The revised approach will be applied on a risk-prioritised, phased basis which will be applied to both UK and non-UK fishing vessels in accordance with the EU requirements. Following the matrix approach described below, management action will focus first on sites that contain features where evidence suggests there is significant risk[4] that certain types of fishing activities could prevent a qualifying feature or sub-feature from achieving its conservation objectives.

7. We intend to proceed on the basis of assessments through a matrix type approach. This shows, at a high generic level, the effect gear types have on the conservation objectives for the relevant features for which EMSs have been selected or designated. This generic matrix ("The Matrix") should provide regulators with an indicator as to whether:-
    a. the activity requires priority management measures to be introduced to protect that feature without further site level assessment on the impacts of that activity on that feature or;
    b. a further assessment may be necessary.

8. Under The Matrix fishing activities will be classed as Red, Amber, Green or Blue according to the potential or actual impact of the gear type on the feature(s) for which a site has been designated. The definition for the classifications is annexed to this paper.

9. For activities identified as Red, the Department would wish management measures to be in place by end 2013, but where this is not practicable, they must have been identified by this date, and implemented by end May 2014. Regulators must inform the Department if they are unable to put measures in place by end 2013. Consideration must be given to the use of emergency byelaw powers where it is clear there is an existing or imminent threat to any Red feature, including cases where a delay in implementation of the revised approach beyond the end of 2013 is expected.

10. For activities identified as Amber a site level assessment will be required to assess whether management of an activity is required to conserve site features. For activities identified as Green, a similar assessment will be needed if there are "in combination effects" with other plans or projects. To carry out such site level assessments the Department's strong preference is for the assessment to be carried out in a manner that is consistent with the provisions of Article 6(3) of the Habitats Directive. Appropriate management measures should be put in place to ensure that fishing activity or activities either have (a) no likely significant effect on a site, having regard to its conservation objectives or (b) that following assessment, have no adverse affect on the integrity of a site. The Department expects such measures to have been identified and put in place by 2016.

11. For sites located between 0-6nm, the Department expects the relevant IFCA to be the lead regulatory authority[5]. For sites between 6-12nm, the MMO should be the lead regulatory authority and measures introduced on a non-discriminatory basis in accordance with the relevant Common Fishery Policy (CFP). Where a site feature straddles the 0-6 and 6-12nm boundary, the expectation is that the MMO will lead.

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[4] Risk relates to the sensitivity of the feature to the type of fishing, and is not related to the level of that fishing activity that may affect that feature.

[5] Except in cases where the Environment Agency is primarily responsible for regulating the fishery

Where a site feature straddles the boundaries between two IFCAs we expect that any management measure proposed for that feature to be consistent across the IFCA boundaries.

Future Fisheries Management

12. By the end of 2016 all fishery operations potentially damaging EMSs should have been identified and be subject to appropriate management. Fishing activity which is prohibited or restricted within EMSs under the revised approach could be allowed through a permitting mechanism at the site level. Any such permitting would be subject to the Article 6(3)-(4) processes described in Part 6 of the Conservation of Habitats and Species Regulations 2010. The regulatory authorities should also ensure ongoing management of commercial fishery activities remains compatible with the conservation objectives of the site in line with their obligations to secure compliance with Article 6(2) of the Habitats Directive. The relevant Statutory Nature Conservation Body has a responsibility to advise the Regulators on this matter.

Management of Sites Requiring Measures in Accordance with the Common Fisheries Policy

13. EMS outside 12nm will require legislative measures to be proposed by the European Commission in accordance with the CFP to ensure adequate protection. For these sites, the Department, taking account of any relevant guidance, intends to submit proposals to the European Commission for any fishery measures needed to ensure site protection is consistent with Article 6 of the Habitats Directive, so that appropriate Regulations are in place in 2016.

DEFRA
24 January 2013

ANNEX

- **RED:** Where it is clear that the conservation objectives for a feature (or sub-feature) will not be achieved because of its sensitivity to a type of fishing, - **irrespective of feature condition, level of pressure, or background environmental conditions in all EMSs where that feature occurs** - suitable management measures will be identified and introduced as a priority to protect those features from that fishing activity or activities.

- **AMBER:** Where there is doubt as to whether conservation objectives for a feature (or sub-feature) will be achieved because of its sensitivity to a type of fishing, **in all EMSs where that feature occurs**, the effect of that activity or activities on such features will need to be assessed in detail at a site specific level. Appropriate management action should then be taken based on that assessment.

- **GREEN:** Where it is clear that the achievement of the conservation objectives for a feature is highly unlikely[6] be affected by a type of fishing activity or activities, in all EMSs where that feature occurs, further action is not likely to be required, unless there is the potential for *in combination* effects[7].

- **BLUE:** For gear types where there can be no feasible interaction[8] between the gear types and habitat features, a fourth categorisation of blue is used, and no management action should be necessary.

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[6] In theory, Green and Amber categories exist along a continuum of risk, for example it is theoretically possible for what is widely recognised to be a benign activity to cause a significant impact on a feature, if carried out at extremely high levels. As result, an assumption has been made that activities categorised as Green are assumed to have no impact on the feature or sub-feature at current maximum levels of commercial fishing effort, to be re-evaluated if conditions change.

[7] In other words, where a type of fishing activity which on its own would not affect the achievement of conservation objectives for the feature, but which in combination with other activities might do so.

[8] On this basis – where there is a feasible (even if unlikely) interaction, activities will be categorised as Red or Amber or Green.

2018 Revision to:

Technical Guidance for Assessing the Effects of Anthropogenic Sound on Marine Mammal Hearing (Version 2.0)

Underwater Thresholds for Onset of Permanent and Temporary Threshold Shifts

Office of Protected Resources
National Marine Fisheries Service
Silver Spring, MD 20910

U.S. Department of Commerce
National Oceanic and Atmospheric Administration
National Marine Fisheries Service

NOAA Technical Memorandum NMFS-OPR-59
April 2018

2018 Revisions to:
Technical Guidance for Assessing the Effects of Anthropogenic Sound on Marine Mammal Hearing
(Version 2.0)

Underwater Thresholds for Onset of Permanent and Temporary Threshold Shifts

NOAA Technical Memorandum NMFS-OPR-59
April 2018

U.S. Department of Commerce
Wilbur Ross, Secretary

National Oceanic and Atmospheric Administration
Tim Gallaudet, Ph.D., USN Ret., Acting Administrator

National Marine Fisheries Service
Chris Oliver, Assistant Administrator for Fisheries

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Copies of this report may be obtained from:

Office of Protected Resources
National Oceanic and Atmospheric Administration
1315 East-West Highway, F/PR2
Silver Spring, MD 20910

Or online at:
NOAA Fisheries Publication web site

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North Atlantic right whales (*Eubalaena glacialis*), Low-frequency cetacean Photo: NOAA
Bottlenose dolphin (*Tursiops truncatus*), Mid-frequency cetacean Photo: Allison Henry (NOAA)
Dall's porpoise (*Phocoenoides dalli*), High-frequency cetacean Photo: Kate Stafford (NOAA)
California sea lion (*Zalophus californianus*), Otariid pinniped Photo: Sharon Melin (NOAA)

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ABBREVIATIONS, ACRONYMS, AND SYMBOLS

a	Low-frequency exponent
ABR	Auditory Brainstem Response
AEP	Auditory Evoked Potentials
AM	Amplitude Modulated
ANSI	American National Standards Institute
b	High-frequency exponent
BOEM	Bureau of Ocean Energy Management
C	Weighting function gain (dB)
CT	Computerized Tomography
D	Duty Cycle
dB	Decibel
PK	Peak sound level
DPOAE	Distortion product otoacoustic emission
$E_{\text{aud}}(f)$	Auditory exposure function
E_0	Exposure Threshold
EEH	Equal Energy Hypothesis
EO	Executive Order
EQL	Equal Loudness
ES	Executive Summary
ESA	Endangered Species Act
f_0	Best hearing (kHz)
f_1	Low-frequency cutoff (kHz)
f_2	High-frequency cutoff (kHz)
G&G	Geological and Geophysical
h	hour
HF	High-frequency
HISA	Highly Influential Scientific Assessment
Hz	Hertz
in^3	Cubic inches
ISI	Influential Scientific Information
ISO	International Organization for Standardization
IQG	Information Quality Guidelines
K	Exposure function gain (dB)
kHz	Kilohertz
LDEO	Lamont-Doherty Earth Observatory
LF	Low-frequency
$L_{0\text{-pk}}$	Peak sound pressure level
$L_{0\text{-pk,flat}}$	Peak sound pressure level (unweighted)
$L_{\text{E,24h}}$	Sound exposure level, cumulative 24h
MF	Mid-frequency
min	Minutes
MMC	Marine Mammal Commission
MMPA	Marine Mammal Protection Act
MSA	Magnuson-Stevens Fishery Conservation and Management Act
MSE	Mean-squared error
m	meter
msec	Milliseconds
NAZ	Narrow Azimuth
NIHL	Noise-induced Hearing Loss
NMFS	National Marine Fisheries Service
NMSA	National Marine Sanctuaries Act
NOAA	National Oceanic and Atmospheric Administration
NOS	National Ocean Service
NRC	National Research Council
NS2	National Standard 2
NSF	National Science Foundation
OMB	Office of Management and Budget
ONMS	Office of National Marine Sanctuaries
OPR	Office of Protected Resources
OSHA	Occupational Safety and Health Administration
OW	Otariids in water
p_0	Sound Pressure Level
Pa	Pascals
π	pi
PK	peak sound pressure level
PTS	Permanent Threshold Shift
PW	Phocids in water
R	Range
R_0	“Safe Distance”
R^2	Goodness of fit
RMS	Root-Mean-Square sound pressure level
S	Source Factor
S_E	Energy Source Factor
s	Seconds
s	Distance from source
s_0	Slope
SEL	Sound exposure level
SEL$_{\text{cum}}$	Cumulative sound exposure level
SIO	Scripps Institution of Oceanography
SL	Source Level

SL_E	Energy Source Level
s_0	Slope (dB/decade)
SPL	Sound Pressure Level
SSC-PAC	SPAWAR Systems Center Pacific
τ	1/repetition rate
TAP	U.S. Navy's Tactical Training Theater Assessment and Planning Program
TS	Threshold Shift
TTS	Temporary Threshold Shift
µPa	Micropascal
μPa^2-s	Micropascal squared second
USFWS	U.S. Fish and Wildlife Service
v	Velocity (transit speed)
$W_{\text{aud}}(f)$	Auditory weighting function
WAZ	Wide Azimuth
WFA	Weighting factor adjustments

EXECUTIVE SUMMARY

This document provides voluntary technical guidance for assessing the effects of underwater anthropogenic (human-made) sound on the hearing of marine mammal species under the jurisdiction of the National Marine Fisheries Service (NMFS) and was completed in collaboration with the National Ocean Service (NOS), Office of National Marine Sanctuaries. Specifically, it identifies the received levels, or thresholds, at which individual marine mammals are predicted to experience changes in their hearing sensitivity (either temporary or permanent) for acute, incidental exposure to underwater anthropogenic sound sources. This Technical Guidance may be used by NMFS analysts/managers and other relevant action proponents/stakeholders, including other federal agencies, when seeking to determine whether and how their activities are expected to result in potential impacts to marine mammal hearing via acoustic exposure. Please note that action proponents have discretion as to whether to use the Technical Guidance; other scientifically rigorous methods are acceptable. This document outlines the development of NMFS' thresholds and describes how they will be updated in the future.

NMFS has compiled, interpreted, and synthesized the scientific literature, including a Technical Report by Dr. James Finneran (U.S. Navy-SPAWAR Systems Center Pacific (SSC-PAC)) (Finneran 2016; Appendix A of this Technical Guidance), to produce thresholds for onset of temporary (TTS) and permanent threshold shifts (PTS) (Table ES2). This document includes a protocol for estimating PTS onset thresholds for impulsive (e.g., airguns, impact pile drivers) and non-impulsive (e.g., tactical sonar, vibratory pile drivers) sound sources, the formation of marine mammal hearing groups (low- (LF), mid- (MF), and high- (HF) frequency cetaceans, and otariid (OW) and phocid (PW) pinnipeds; Table ES1), and the incorporation of marine mammal auditory weighting functions (Figures ES1 and ES2) into the derivation of PTS onset thresholds. These thresholds are presented using dual metrics of weighted cumulative sound exposure level ($\mathrm{SEL}_{\mathrm{cum}}$) and peak sound level (PK) for impulsive sounds and weighted $\mathrm{SEL}_{\mathrm{cum}}$ for non-impulsive sounds.

While the Technical Guidance's thresholds are more complex than those used to date in most cases by NMFS, they reflect the current state of scientific knowledge regarding the characteristics of sound that have the potential to impact marine mammal hearing sensitivity. NMFS recognizes that the implementation of marine mammal weighting functions and the weighted $\mathrm{SEL}_{\mathrm{cum}}$ metric represent new factors for consideration, which may extend beyond the capabilities of some action proponents. Thus, NMFS has developed alternative tools for those who cannot fully incorporate these factors (See Appendix D, Technical Guidance's companion User Spreadsheet tool[1], and recently developed User Spreadsheet Manual (NMFS 2018)[1]).

These thresholds do not represent the entirety of a comprehensive analysis of the effects of a proposed action, but rather serve as one tool (along with, e.g., behavioral impact thresholds, auditory masking assessments, evaluations to help understand the ultimate effects of any particular type of impact on an individual's fitness, population assessments, etc.) to help evaluate the effects of a proposed action and make the relevant findings required by NOAA's various statutes. The Technical Guidance may inform decisions related to mitigation and monitoring requirements, but it does not mandate any specific mitigation be required. The Technical Guidance does not address or change NMFS' application of these thresholds in the regulatory context, under applicable statutes and does not create or confer any rights for or on any person, or operate to bind the public. It only updates NMFS' thresholds based on the most recent science.

This Technical Guidance is classified as a Highly Influential Scientific Assessment (HISA) by the President's Office of Management and Budget (OMB). As such, independent peer review was required prior to broad public dissemination by the Federal Government. Details of the three peer reviews, associated with the Technical Guidance, are within this document (Appendix C).

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[1] Link to Technical Guidance web page.

REVISIONS TO 2016 TECHNICAL GUIDANCE

Presidential Executive Order (EO) 13795, Implementing an America-First Offshore Energy Strategy (82 FR 20815; April 28, 2017), states in section 2 that “It shall be the policy of the United States to encourage energy exploration and production, including on the Outer Continental Shelf, in order to maintain the Nation’s position as a global energy leader and foster energy security and resilience for the benefit of the American people, while ensuring that any such activity is safe and environmentally responsible.” Section 10 of the E.O. called for a review of the 2016 Technical Guidance for Assessing the Effects of Anthropogenic Sound on Marine Mammal Hearing (Technical Guidance; NMFS 2016a) as follows: “The Secretary of Commerce shall review [Technical Guidance] for consistency with the policy set forth in Section 2 of this order and, after consultation with the appropriate Federal agencies, take all steps permitted by law to rescind or revise that guidance, if appropriate.”

To assist the Secretary in carrying out the directive under EO 13795, NMFS held a 45-day public comment period (82 FR 24950; May 31, 2017) and a Federal Interagency Consultation (September 25, 2017) to solicit comments on the Technical Guidance for consistency with the EO’s policy.

Many of the comments NMFS received, including those from Federal agencies, were supportive of the Technical Guidance, including the science used in its derivation and the robust process that NMFS followed, including four independent peer reviews. The majority of commenters recommended that the Technical Guidance remain unchanged. The Federal agencies, Members of Congress, and subject matter experts expressed support for the Technical Guidance as reflecting the best available science. NMFS received no recommendations to rescind the 2016 Technical Guidance. The majority of comments pertained to recommendations to improve implementation of the Technical Guidance, rather than the Technical Guidance itself, or were beyond the scope of the Technical Guidance and/or its review under section 10 of EO 13795.

NMFS’ evaluation of comments received during this process affirmed that the Technical Guidance is based on upon the best available science. However, to facilitate its use and implementation, NMFS revised the 2016 Technical Guidance (NMFS 2016a), per approval of the Secretary of Commerce, to provide improvements and clarification on implementation of the document (i.e., 2018 Revised Technical Guidance, Version 2.0).

SUMMARY OF TECHNICAL ASPECTS

This document is organized so that the most pertinent information can be found easily in the main body. Additional details are provided in the appendices. Section I introduces the document. NMFS’ thresholds for onset of PTS for marine mammals exposed to underwater sound are presented in Section II. NMFS’ plan for periodically updating thresholds is presented in Section III. More details on the development of thresholds, the peer review and public comment process, research recommendations, alternative methodology, and a glossary of acoustic terms are found in the appendices.

The following Tables and Figures summarize the three main aspects of the Technical Guidance: 1) Marine mammal hearing groups (Table ES1); 2) Marine mammal auditory weighting functions (Figures ES1 and ES2; Table ES2); and PTS onset thresholds (Table ES3).

Table ES1: Marine mammal hearing groups.

Hearing Group	Generalized Hearing Range*
Low-frequency (LF) cetaceans (baleen whales)	7 Hz to 35 kHz
Mid-frequency (MF) cetaceans (dolphins, toothed whales, beaked whales, bottlenose whales)	150 Hz to 160 kHz
High-frequency (HF) cetaceans (true porpoises, *Kogia*, river dolphins, cephalorhynchid, *Lagenorhynchus cruciger* & *L. australis*)	275 Hz to 160 kHz
Phocid pinnipeds (PW) (underwater) (true seals)	50 Hz to 86 kHz
Otariid pinnipeds (OW) (underwater) (sea lions and fur seals)	60 Hz to 39 kHz

***** Represents the generalized hearing range for the entire group as a composite (i.e., all species within the group), where individual species' hearing ranges are typically not as broad. Generalized hearing range chosen based on ~65 dB threshold from normalized composite audiogram, with the exception for lower limits for LF cetaceans (Southall et al. 2007) and PW pinniped (approximation).

Table ES2: Summary of auditory weighting and exposure function parameters.*

Hearing Group	a	b	f_1 (kHz)	f_2 (kHz)	C (dB)	K (dB)
Low-frequency (LF) cetaceans	1.0	2	0.2	19	0.13	179
Mid-frequency (MF) cetaceans	1.6	2	8.8	110	1.20	177
High-frequency (HF) cetaceans	1.8	2	12	140	1.36	152
Phocid pinnipeds (PW) (underwater)	1.0	2	1.9	30	0.75	180
Otariid pinnipeds (OW) (underwater)	2.0	2	0.94	25	0.64	198

* Equations associated with Technical Guidance's auditory weighting ($W_{\text{aud}}(f)$) and exposure functions ($E_{\text{aud}}(f)$):

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

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

Table ES3: Summary of PTS onset thresholds.

	PTS Onset Thresholds* (Received Level)	
Hearing Group	**Impulsive**	**Non-impulsive**
Low-Frequency (LF) Cetaceans	*Cell 1* $L_{p,\text{0-pk,flat}}$: 219 dB $L_{\text{E},p,\text{ LF,24h}}$: 183 dB	*Cell 2* $L_{\text{E},p,\text{ LF,24h}}$: 199 dB
Mid-Frequency (MF) Cetaceans	*Cell 3* $L_{p,\text{0-pk,flat}}$: 230 dB $L_{\text{E},p,\text{ MF,24h}}$: 185 dB	*Cell 4* $L_{\text{E},p,\text{ MF,24h}}$: 198 dB
High-Frequency (HF) Cetaceans	*Cell 5* $L_{p,\text{0-pk,flat}}$: 202 dB $L_{\text{E},p,\text{HF,24h}}$: 155 dB	*Cell 6* $L_{\text{E},p,\text{ HF,24h}}$: 173 dB
Phocid Pinnipeds (PW) (Underwater)	*Cell 7* $L_{p,\text{0-pk.flat}}$: 218 dB $L_{\text{E},p,\text{PW,24h}}$: 185 dB	*Cell 8* $L_{\text{E},p,\text{PW,24h}}$: 201 dB
Otariid Pinnipeds (OW) (Underwater)	*Cell 9* $L_{p,\text{0-pk,flat}}$: 232 dB $L_{\text{E},p,\text{OW,24h}}$: 203 dB	*Cell 10* $L_{\text{E},p,\text{OW,24h}}$: 219 dB

* Dual metric thresholds for impulsive sounds: Use whichever results in the largest isopleth for calculating PTS onset. If a non-impulsive sound has the potential of exceeding the peak sound pressure level thresholds associated with impulsive sounds, these thresholds are recommended for consideration.

Note: Peak sound pressure level ($L_{p,\text{0-pk}}$) has a reference value of 1 µPa, and weighted cumulative sound exposure level ($L_{\text{E},p}$) has a reference value of 1µPa^{2}s. In this Table, thresholds are abbreviated to be more reflective of International Organization for Standardization standards (ISO 2017). The subscript “flat” is being included to indicate peak sound pressure are flat weighted or unweighted within the generalized hearing range of marine mammals (i.e., 7 Hz to 160 kHz). The subscript associated with cumulative sound exposure level thresholds indicates the designated marine mammal auditory weighting function (LF, MF, and HF cetaceans, and PW and OW pinnipeds) and that the recommended accumulation period is 24 hours. The weighted cumulative sound exposure level thresholds could be exceeded in a multitude of ways (i.e., varying exposure levels and durations, duty cycle). When possible, it is valuable for action proponents to indicate the conditions under which these thresholds will be exceeded.

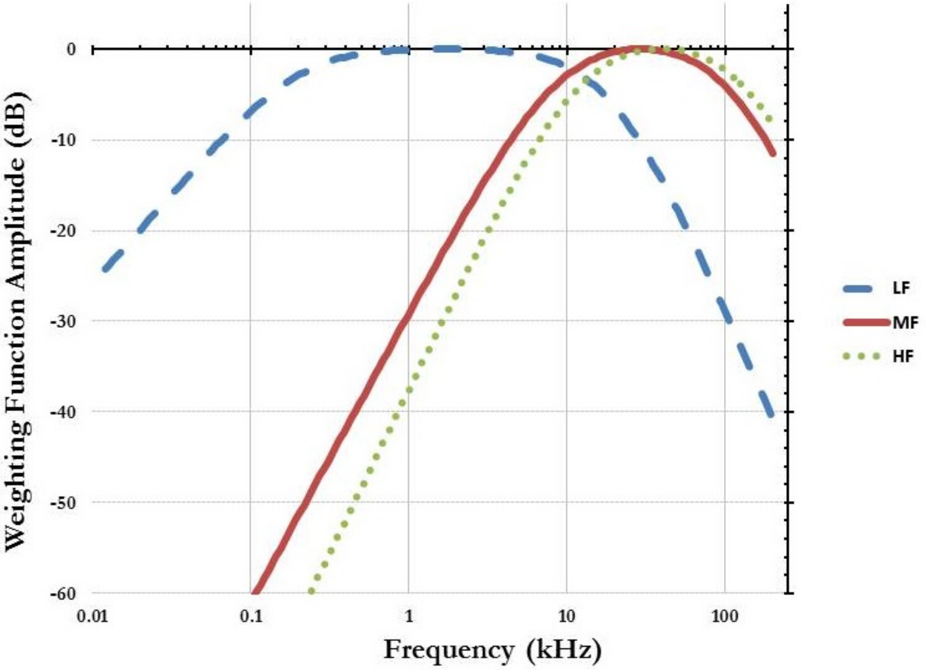

Figure ES1: Auditory weighting functions for low-frequency (LF; dashed line), mid-frequency (MF; solid line), and high-frequency (HF; dotted line) cetaceans.

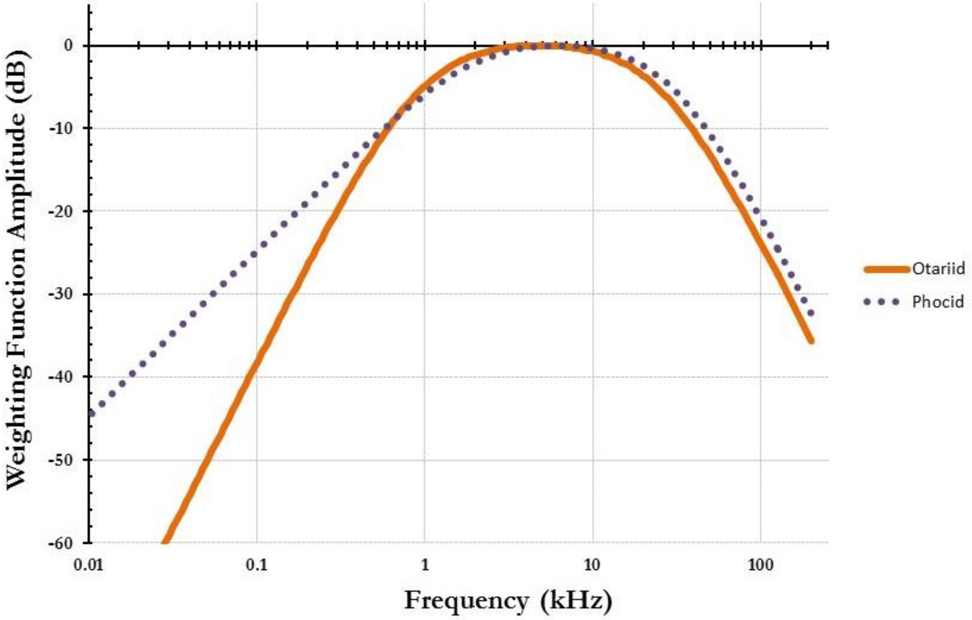

Figure ES2: Underwater auditory weighting functions for otariid (OW; solid line) and phocid (PW; dotted line) pinnipeds.

REVISION TO: TECHNICAL GUIDANCE FOR ASSESSING THE EFFECTS OF ANTHROPOGENIC SOUND ON MARINE MAMMAL HEARING (VERSION 2.0)

UNDERWATER THRESHOLDS FOR ONSET OF PERMANENT AND TEMPORARY THRESHOLD SHIFTS

I. INTRODUCTION

This document provides technical guidance[2] for assessing the effects of anthropogenic (human-made) sound on the hearing of marine mammal species under the jurisdiction[3] of the National Marine Fisheries Service (NMFS) and was completed in collaboration with the National Ocean Service (NOS), Office of National Marine Sanctuaries. Specifically, it identifies the received levels, or thresholds, at which individual marine mammals are predicted to experience changes in their hearing sensitivity for acute, incidental exposure to all underwater anthropogenic sound sources. This Technical Guidance is intended for use by NMFS analysts/ managers and other relevant action proponents/stakeholders, including other federal agencies, when seeking to determine whether and how their activities are expected to result in impacts to marine mammal hearing via acoustic exposure. This document outlines NMFS' thresholds, describing in detail threshold development (via Appendix A), and how they will be revised and updated in the future.

The thresholds presented in this document do not represent the entirety of an effects analysis, but rather serve as one tool among others (e.g., behavioral impact thresholds, auditory masking assessments, evaluations to help understand the effects of any particular type of impact on an individual's fitness, population assessments, etc.), to help evaluate the effects of a proposed action and make findings required by NOAA's various statutes. The Technical Guidance may inform decisions related to mitigation and monitoring requirements, but it does not mandate any specific mitigation be required[4]. The Technical Guidance does not address or change NMFS' application of these thresholds in the regulatory context, under applicable statutes and does not create or confer any rights for or on any person, or operate to bind the public. It only updates NMFS' thresholds based on the most recent science.

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[2] The use of the Technical Guidance is not mandatory; it does not create or confer any rights for or on any person, or operate to bind the public. An alternative approach that has undergone independent peer review may be proposed (by federal agencies or prospective action proponents) and used if case-specific information/data indicate that the alternative approach is likely to produce a more accurate estimate of auditory impact for the project being evaluated; and if NMFS determines the approach satisfies the requirements of the applicable statutes and regulations.

[3] Link to marine mammals under NMFS' jurisdiction. This document does not pertain to marine mammal species under the U.S. Fish and Wildlife Service's (USFWS) jurisdiction (e.g., walrus, polar bears, West Indian manatees, sea otters). However, since marine mammal audiogram data are limited, a decision was made to include all available datasets from in-water groups, including sirenian datasets (Gerstein et al. 1999; Mann et al. 2009), to derive composite audiogram parameters and threshold of best hearing for LF cetaceans (see Appendix A_1). Additionally, audiogram data from a single Pacific walrus (Kastelein et al. 2002) and a single sea otter (Ghoul and Reichmuth 2014) were included in the derivation of the composite audiogram for OW pinnipeds.

[4] Mitigation and monitoring requirements associated with a Marine Mammal Protection Act (MMPA) authorization or an Endangered Species Act (ESA) consultation or permit are independent management decisions made in the context of the proposed activity and comprehensive effects analysis, and are beyond the scope of the Technical Guidance. NMFS acknowledges exclusion zones and monitoring zones often correspond to thresholds but that is not a legal requirement, and the thresholds may make such a simple correlation more challenging. The Technical Guidance can be used to inform the development of mitigation or monitoring. NMFS is currently developing a separate document further describing how the Technical Guidance is used in the MMPA authorization process to inform mitigation decisions. This document, when available, can be found at: NMFS Incidental Take Authorization web page.

Note: This document does not set forth requirements to conduct sound source verification studies.

1.1. THRESHOLDS WITHIN THE CONTEXT OF AN EFFECTS ANALYSIS

The Technical Guidance's thresholds do not represent the entirety of an effects analysis, but rather serve as one tool to help evaluate the effects of sound produced during a proposed action on marine mammals and make findings required by NOAA's various statutes. In a regulatory context, NMFS uses thresholds to help assess and quantify "take" and to conduct more comprehensive effects analyses under several statutes. NMFS is currently developing a separate document[5] further describing how the Technical Guidance is used in the MMPA authorization process to estimate "take."

Specifically, the Technical Guidance will be used in conjunction with sound source characteristics, environmental factors that influence sound propagation, anticipated marine mammal occurrence and behavior near the activity, as well as other available activity-specific factors, to estimate the number and types of takes of marine mammals. This document only addresses thresholds for auditory impact (i.e., does not address or make recommendations associated with sound propagation or marine mammal occurrence or density).

1.2 ADDRESSING UNCERTAINTY AND DATA LIMITATIONS

Inherent data limitations occur in many instances when assessing acoustic effects on marine mammal hearing. Data limitations, which make it difficult to account for uncertainty and variability, are not unique to assessing the effects of anthropogenic sound on marine mammals and are commonly encountered by resource managers (Ludwig et al. 1993; Francis and Shotton 1997; Harwood and Stokes 2003; Punt and Donovan 2007). Southall et al. (2007) and Finneran (2016) acknowledged the inherent data limitations when making recommendations for criteria to assess the effects of noise on marine mammals, including data available from a limited number of species, a limited number of individuals within a species, and/or limited number of sound sources. Both Finneran (2016) and Southall et al. (2007) applied certain extrapolation procedures to estimate effects that had not been directly measured but that could be reasonably approximated using existing information and reasoned logic. The Technical Guidance articulates where NMFS has faced such uncertainty and variability in the development of its thresholds.

1.2.1 Assessment Framework

NMFS' approach applies a set of assumptions to address uncertainty in predicting potential auditory effects of sound on individual marine mammals. One of these assumptions includes the use of "representative" or surrogate individuals/species for establishing PTS onset thresholds for species where little to no data exists. The use of representative individuals/species is done as a matter of practicality (i.e., it is unlikely that adequate data will exist for the all marine mammal species found worldwide or that we will be able to account for all sources of variability at an individual level) but is also scientifically based (i.e., taxonomy, hearing group). As new data become available for more species, this approach can be reevaluated. NMFS recognizes that additional applicable data may become available to better address many of these issues (e.g., uncertainty, surrogate species, etc.).[6] As these new data become available, NMFS has an approach for updating this document (see Section III).

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[5] Document, when available, can be found at: NMFS Incidental Take Authorization web page.

[6] NMFS is aware that the authors of Southall et al. (2007) are in the process of updating their original publication and recognizes that when this updated publication becomes available, it may suggest alternative means for predicting an

1.2.2 Data Standards

In assessing potential acoustic effects on marine mammals, as with any such issue facing the agency, standards for determining applicable data need to be articulated. Specifically, NOAA has Information Quality Guidelines[7] (IQG) for “ensuring and maximizing the quality, objectivity, utility, and integrity of information disseminated by the agency” (with each of these terms defined within the IQG). Further, the IQG stipulate that “To the degree that the agency action is based on science, NMFS will use (a) the best available science and supporting studies (including peer-reviewed science and supporting studies when available), conducted in accordance with sound and objective scientific practices, and (b) data collected by accepted methods or best available methods.”

The National Research Council (NRC 2004) provided basic guidelines for National Standard 2 (NS2) in section 301 of the Magnuson-Stevens Fishery Conservation and Management Act, which states that “Conservation and management measures shall be based upon the best scientific information available” (NOAA 2013). They recommended that data underlying the decision-making and/or policy-setting process be: 1) relevant, 2) inclusive, 3) objective, 4) transparent and open, 5) timely, 6) verified and validated, and 7) peer reviewed.[8] Although NRC’s guidelines (NRC 2004) were not written specifically for marine mammals and this particular issue, they do provide a means of articulating minimum data standards. NMFS considered this in assessing acoustic effects on marine mammals. Use of the NRC Guidelines does not preclude development of acoustic-specific data standards in the future.

II. NMFS’ THRESHOLDS FOR ONSET OF PERMANENT THRESHOLD SHIFTS IN MARINE MAMMALS

The Technical Guidance advances NMFS’ assessment ability based upon the compilation, interpretation, and synthesis of the scientific literature. This document provides thresholds for the onset of PTS based on characteristics defined at the acoustic source. No direct measurements of marine mammal PTS have been published; PTS onset thresholds have been extrapolated from marine mammal TTS measurements (i.e., using growth rates from terrestrial and marine mammal data). PTS onset thresholds, for all sound sources are divided into two broad categories: 1) impulsive and 2) non-impulsive. Thresholds are also presented as dual metric thresholds using weighted cumulative sound exposure level ($\mathrm{SEL}_{\mathrm{cum},}$) and peak sound pressure (PK) metrics for impulsive sounds. As dual metrics, NMFS considers onset of PTS to have occurred when either one of the two metrics is exceeded. For non-impulsive sounds, thresholds are provided using the weighted $\mathrm{SEL}_{\mathrm{cum}}$ metric. Additionally, to account for the fact that different species groups use and hear sound differently, marine mammals are sub-divided into five broad hearing groups (i.e., LF, MF, HF, PW, and OW) and thresholds in the weighted $\mathrm{SEL}_{\mathrm{cum}}$ metric incorporate auditory weighting functions.

2.1 MARINE MAMMAL HEARING GROUPS

Current data (via direct behavioral and electrophysiological measurements) and predictions (based on inner ear morphology, modeling, behavior, vocalizations, or taxonomy) indicate that not

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auditory weighting function and thresholds for LF cetaceans. Accordingly, NMFS may re-evaluate our methodology for LF cetaceans when this updated Southall et al. publication becomes available.

[7] NMFS National Standards 2 web page.

[8] NMFS also requires Peer Review Plans for Highly Influential Scientific Assessments (HISA) and Influential Scientific Information (ISI).

all marine mammal species have equal hearing capabilities, in terms of absolute hearing sensitivity and the frequency band of hearing (Richardson et al. 1995; Wartzok and Ketten 1999; Southall et al. 2007; Au and Hastings 2008). Hearing has been directly measured in some odontocete and pinniped species[9] (see reviews in Southall et al. 2007; Erbe et al. 2016; Finneran 2016). Direct measurements of mysticete hearing are lacking.[10] Thus, hearing predictions for mysticetes are based on other methods including: anatomical studies and modeling (Houser et al. 2001; Parks et al. 2007; Tubelli et al. 2012; Cranford and Krysl 2015[11]); vocalizations[12] (see reviews in Richardson et al. 1995; Wartzok and Ketten 1999; Au and Hastings 2008); taxonomy; and behavioral responses to sound (Dahlheim and Ljungblad 1990; see review in Reichmuth 2007).

To better reflect marine mammal hearing capabilities, Southall et al. (2007) recommended that marine mammals be divided into hearing groups (Table 1). NMFS made the following modifications to the hearing groups proposed in Southall et al. (2007)[13]:

- <u>Division of pinnipeds into PW and OW hearing groups</u>: NMFS subdivided pinnipeds into their two families: Phocidae and Otariidae. Based on a review of the literature, phocid species have consistently demonstrated an extended frequency range of hearing compared to otariids, especially in the higher frequency range (Hemilä et al. 2006; Kastelein et al. 2009a; Reichmuth et al. 2013). Phocid ears are anatomically distinct from otariid ears in that phocids have larger, more dense middle ear ossicles, inflated auditory bulla, and larger sections of the inner ear (i.e., tympanic membrane, oval window, and round window), which make them more adapted for underwater hearing (Terhune and Ronald 1975; Schusterman and Moore 1978; Kastak and Schusterman 1998; Hemilä et al. 2006; Mulsow et al. 2011; Reichmuth et al. 2013).

- <u>Recategorization of hourglass (*Lagenorhynchus cruciger*) and Peale's (*L. australis*) dolphins from MF cetacean to HF cetacean hearing group:</u> Echolocation data (Kyhn et al. 2009; Kyhn et al. 2010; Tougaard and Kyhn. 2010) indicate that the hourglass and Peale's dolphin produce sounds (i.e., higher mean peak frequency) similar to other narrow band high-frequency cetaceans, such as porpoises, *Kogia*, and *Cephalorhynchus*, and are distinctly different from other *Lagenorhynchus* species. Genetic data also suggest these two species are more closely related to *Cephalorhynchus* species (May-Collado and Agnarsson 2006). Thus, based on this information, NMFS has decided to move these two species from MF cetaceans to HF cetaceans.

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[9] Hearing measurements both in air and underwater have been collected for pinniped species.

[10] There was an unsuccessful attempt to directly measure hearing in a stranded gray whale calf by Ridgway and Carder 2001.

[11] <u>Note</u>: The modeling of Cranford and Krsyl (2015) predicts that the primary mechanism for hearing in LF cetaceans is bone conduction. Additionally, this predictive model was based on the skull geometry of a newborn fin whale.

[12] Studies in other species indicate that perception of frequencies may be broader than frequencies produced (e.g., Luther and Wiley 2009).

[13] NMFS considered dividing LF cetaceans into two separate groups (i.e., some species may have better low frequency hearing than others, like blue and fin whales; Clark and Ellison 2004), but decided there was not enough data to support such a division at this time. NMFS also considered separating sperm whales from other MF cetaceans, but there are not enough data are available to stipulate exactly how to do this. Sperm whale placement within MF cetaceans is considered appropriate based on Ketten (2000), which classified sperm whales as having Type I cochlea, similar to other MF cetaceans.

Table 1: Marine mammal hearing groups.

Hearing Group	Generalized Hearing Range*
Low-frequency (LF) cetaceans (baleen whales)	7 Hz to 35 kHz
Mid-frequency (MF) cetaceans (dolphins, toothed whales, beaked whales, bottlenose whales)	150 Hz to 160 kHz
High-frequency (HF) cetaceans (true porpoises, *Kogia*, river dolphins, cephalorhynchid, *Lagenorhynchus cruciger* & *L. australis*)	275 Hz to 160 kHz
Phocid pinnipeds (PW) (underwater) (true seals)	50 Hz to 86 kHz
Otariid pinnipeds (OW) (underwater) (sea lions and fur seals)	60 Hz to 39 kHz

***** Represents the generalized hearing range for the entire group as a composite (i.e., all species within the group), where individual species' hearing ranges are typically not as broad. Generalized hearing range chosen based on ~65 dB threshold from normalized composite audiogram, with the exception for lower limits for LF cetaceans (Southall et al. 2007) and PW pinniped (approximation).

NMFS' modification results in marine mammal hearing groups being defined in this Technical Guidance as depicted in Table 1. Table 1 defines a generalized hearing range each hearing group. This generalized hearing range was determined based on the ~65 dB[14] threshold from the normalized composite audiograms (Figure 4). For LF cetaceans and PW pinnipeds, the ~65 dB threshold resulted in a lower bound that was considered too low to be biologically plausible for these two groups. Instead, for LF cetaceans the lower frequency limit from Southall et al. 2007 was used, while for PW pinnipeds 50 Hz was chosen as a reasonable approximation for the lower frequency limit (relative to otariid pinnipeds)[15].

2.1.1 Application of Marine Mammal Hearing Groups

The application of marine mammal hearing groups occurs throughout the Technical Guidance in two ways. First, thresholds are divided by hearing group to acknowledge that not all marine mammal species have identical hearing or susceptibility to noise-induced hearing loss (NIHL). Outside the generalized hearing range, the risk of auditory impacts from sounds is considered highly unlikely or very low[16] (the exception would be if a sound above/below this range has the potential to cause physical injury, i.e., lung or gastrointestinal tract injury from underwater explosives).

Second, marine mammal hearing groups are used in the establishment of marine mammal auditory weighting functions discussed next.

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[14] In humans, functional hearing range is typically defined as 60 dB above the hearing threshold at greatest hearing sensitivity. To account for uncertainty associated with marine mammal hearing, NMFS based the Technical Guidance's generalized hearing range on 65 dB.

[15] Understanding of low-frequency pinniped hearing is limited (i.e., few studies have direct measurements of hearing below 100 Hz).

[16] Animals are able to detect sounds beyond their generalized hearing range by non-auditory mechanisms. However, typically, these sounds have to be extremely loud and would be considered uncomfortable (Wartzok and Ketten 1999). If a sound is on the edge of a hearing group's generalized hearing range and there is the potential for exposure to high sound pressure levels, then consider the potential for detection beyond normal auditory pathways.

2.2 MARINE MAMMAL AUDITORY WEIGHTING FUNCTIONS

The ability to hear sounds varies across a species' hearing range. Most mammal audiograms have a typical "U-shape," with frequencies at the bottom of the "U" being those to which the animal is more sensitive, in terms of hearing (i.e. the animal's best hearing range; for example audiogram, see Glossary, Figure F1). Auditory weighting functions best reflect an animal's ability to hear a sound (and do not necessarily reflect how an animal will perceive and behaviorally react to that sound). To reflect higher hearing sensitivity at particular frequencies, sounds are often weighted. For example, A-weighting for humans deemphasize frequencies below 1 kHz and above 6 kHz based on the inverse of the idealized (smoothed) 40-phon equal loudness hearing function across frequencies, standardized to 0 dB at 1 kHz (e.g., Harris 1998). Other types of weighting functions for humans (e.g., B, C, D) deemphasize different frequencies to different extremes (e.g., flattens equal-loudness perception across wider frequencies with increasing received level; for example, C-weighting is uniform from 50 Hz to 5 kHz; ANSI 2011).

Auditory weighting functions have been proposed for marine mammals, specifically associated with PTS onset thresholds expressed in the weighted SEL_{cum} [17] metric, which take into account what is known about marine mammal hearing (Southall et al. 2007; Erbe et al. 2016). The Finneran Technical Report (Finneran 2016) developed marine mammal auditory weighting functions that reflect new data on:

- Marine mammal hearing (e.g., Sills et al. 2014; Sills et al. 2015; Cranford and Krysl, 2015; Kastelein et al. 2015c)

- Marine mammal equal latency contours (e.g., Reichmuth 2013; Wensveen et al. 2014; Mulsow et al. 2015

- Effects of noise on marine mammal hearing (e.g., Kastelein et al. 2012a; Kastelein et al. 2012b; Finneran and Schlundt 2013; Kastelein et al. 2013a; Kastelein et al. 2013b; Popov et al. 2013; Kastelein et al. 2014a; Kastelein et al. 2014b; Popov et al. 2014; Finneran et al. 2015; Kastelein et al., 2015a; Kastelein et al. 2015b; Popov et al. 2015).

This reflects a transition from auditory weighting functions that have previously been more similar to human dB(C) functions (i.e., M-weighting from Southall et al. 2007) to that more similar to human dB(A) functions. These marine mammal auditory weighting functions also provide a more consistent approach/methodology for all hearing groups.

Upon evaluation, NMFS determined that the proposed methodology in Finneran 2016 reflects the scientific literature and incorporated it directly into this Technical Guidance (Appendix A) following an independent peer review (see Appendix C for details on peer review and link to Peer Review Report).

2.2.1 Use of Auditory Weighting Functions in Assessing Susceptibility to Noise-Induced Hearing Loss

Auditory weighting functions are used for human noise standards to assess the overall hazard of noise on hearing. Specifically, human auditory weighting functions provide a "rating that indicates the injurious effects of noise on human hearing" (OSHA 2013). Thus, while these functions are based on regions of equal loudness and best hearing, in the context of human risk assessments, as well as their use in the Technical Guidance, they are meant to reflect the susceptibility of the ear to noise-induced threshold shifts (TSs). Regions of enhanced susceptibility to noise may not

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[17] Auditory weighting functions are not to be applied to PTS or TTS onset thresholds expressed as the PK metric (i.e., PK thresholds are flat or unweighted within the generalized hearing range). For more information, please see Section 2.3.2.2.

perfectly mirror a species' region of best hearing (e.g., TTS measurements from bottlenose dolphin, belugas, and Yangtze finless porpoise support this). Thus, within the Technical Guidance, auditory weighting functions are meant to assess risk of NIHL and do not necessarily encompass the entire range of best hearing for every species within the hearing group.

2.2.2 Marine Mammal Auditory Weighting Functions

Frequency-dependent marine mammal auditory weighting functions were derived using data on hearing ability (composite audiograms), effects of noise on hearing, and data on equal latency (Finneran 2016[18]). Separate functions were derived for each marine mammal hearing group (Figures 1 and 2).

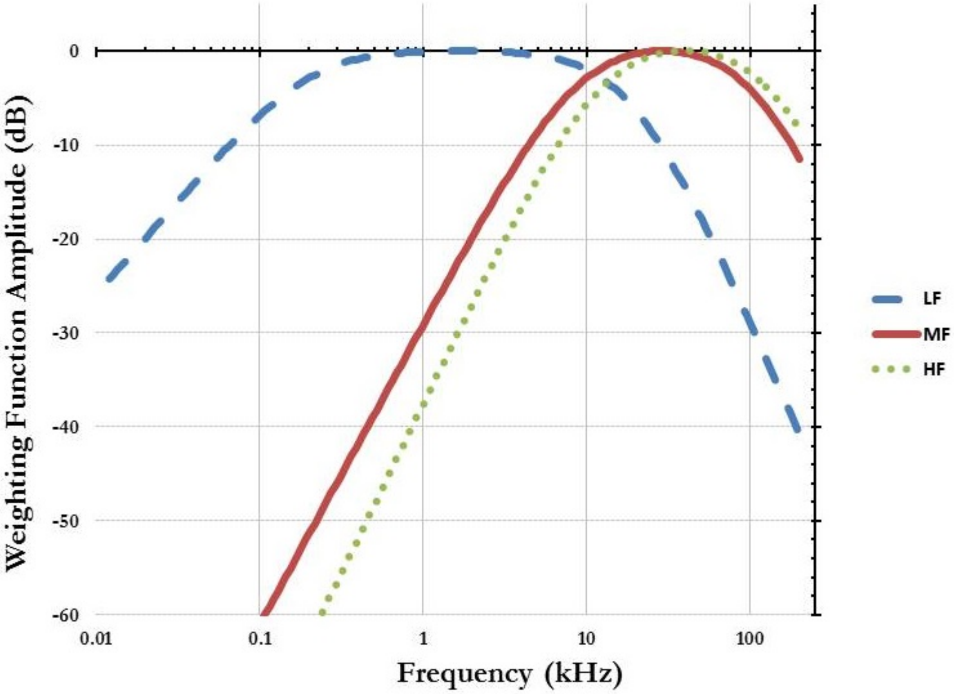

Figure 1: **Auditory weighting functions for low-frequency (LF; dashed line), mid-frequency (MF; solid line), and high-frequency (HF; dotted line) cetaceans.**

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[18] Wright 2015 provides a critique of this methodology. For NMFS' response associated with this critique, see the Federal Register Notice associated with 2016 Technical Guidance (81 FR 51694; August 4, 2016), specifically the section responding to public comments.

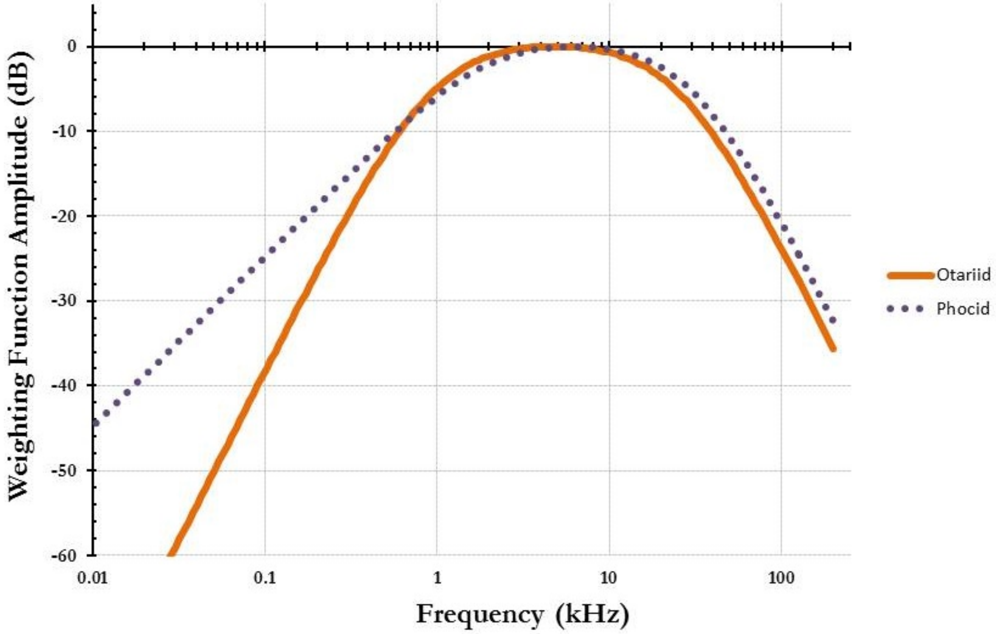

Figure 2: **Underwater auditory weighting functions for otariid (OW; solid line) and phocid (PW; dotted line) pinnipeds.**

The overall shape of the auditory weighting functions is based on a generic band-pass filter described by Equation 1:

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

where $W_{aud}(f)$ is the auditory weighting function amplitude in decibels (dB) at a particular frequency (f) in kilohertz (kHz). The function shape is determined by the following auditory weighting function parameters:

- Low-frequency exponent (a): This parameter determines the rate at which the weighting function amplitude declines with frequency at the lower frequencies. As the frequency decreases, the change in amplitude becomes linear with the logarithm of frequency with a slope of $20a$ dB/decade.

- High-frequency exponent (b): Rate at which the weighting function amplitude declines with frequency at the upper frequencies. As the frequency increases, the change in amplitude becomes linear with the logarithm of frequency with a slope of $20b$ dB/decade.

- Low-frequency cutoff (f_1): This parameter defines the lower limit of the band-pass filter (i.e., the lower frequency where weighting function amplitude begins to roll off or decline from the flat, central portion of the function). This parameter is directly dependent on the value of the low-frequency exponent (a).

- High-frequency cutoff (f_2): This parameter defines the upper limit the band-pass filter (i.e., the upper frequency where weighting function amplitude begins to roll off or decline from the flat, central portion of the function). This parameter is directly dependent on the value of the high-frequency exponent (b).

- Weighting function gain (C): This parameter determines the vertical position of the function and is adjusted to set the maximum amplitude of the auditory weighting function to 0 dB.

Finneran (2016) illustrates the influence of each parameter value on the shape of the auditory weighting function (Appendix A, Figure A2).

In association with auditory weighting functions are exposure functions that illustrate how auditory weighting functions relate to auditory thresholds. Auditory exposure functions (Equation 2) are the inversion of Equation 1:

$$E_{\text{aud}}(f) = K - 10\log_{10}\left\{\frac{(f/f_1)^{2a}}{\left[1+(f/f_1)^2\right]^a\left[1+(f/f_2)^2\right]^b}\right\} \qquad \text{dB}$$

Equation 2

where $E_{\text{aud}}(f)$ is the acoustic exposure as a function of frequency (f) and the gain parameter constant (K), which is adjusted to set the minimum value of the curve to the weighted PTS/TTS onset auditory threshold. All other parameters are the same as those in Equation 1. Figure 3 illustrates how the various weighting parameters relate to one another in both the auditory weighting and exposure functions.

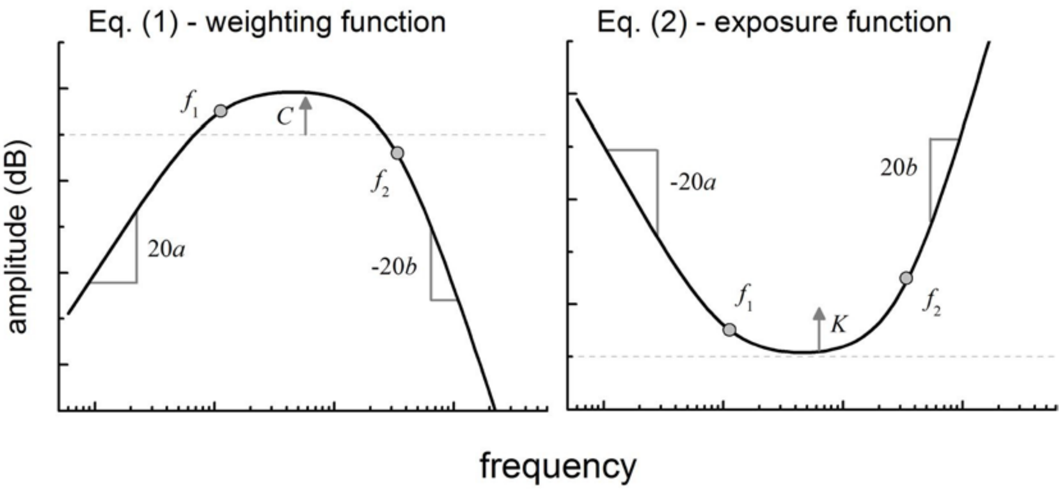

Figure 3: **Illustration of function parameter in both auditory weighting functions and exposure functions (from Finneran 2016). Reference to Equations 1 and 2 match those in the Technical Guidance.**

Finneran (2016) (Appendix A, Figures A-22 and A-23) provides a comparison of these auditory weighting functions with previously derived weighting functions (Finneran and Jenkins 2012 used in Navy Phase 2 Analysis).

2.2.3 Derivation of Function Parameters

Numeric values associated with auditory weighting function parameters were derived from available data from audiograms (measured and predicted), equal latency contours, and marine mammal TTS data using the following steps from Finneran (2016):

1. Derivation of marine mammal composite audiograms (original and normalized) for each hearing group (Resulting normalized composite audiogram: Figure 4; Data sources: Table 2).

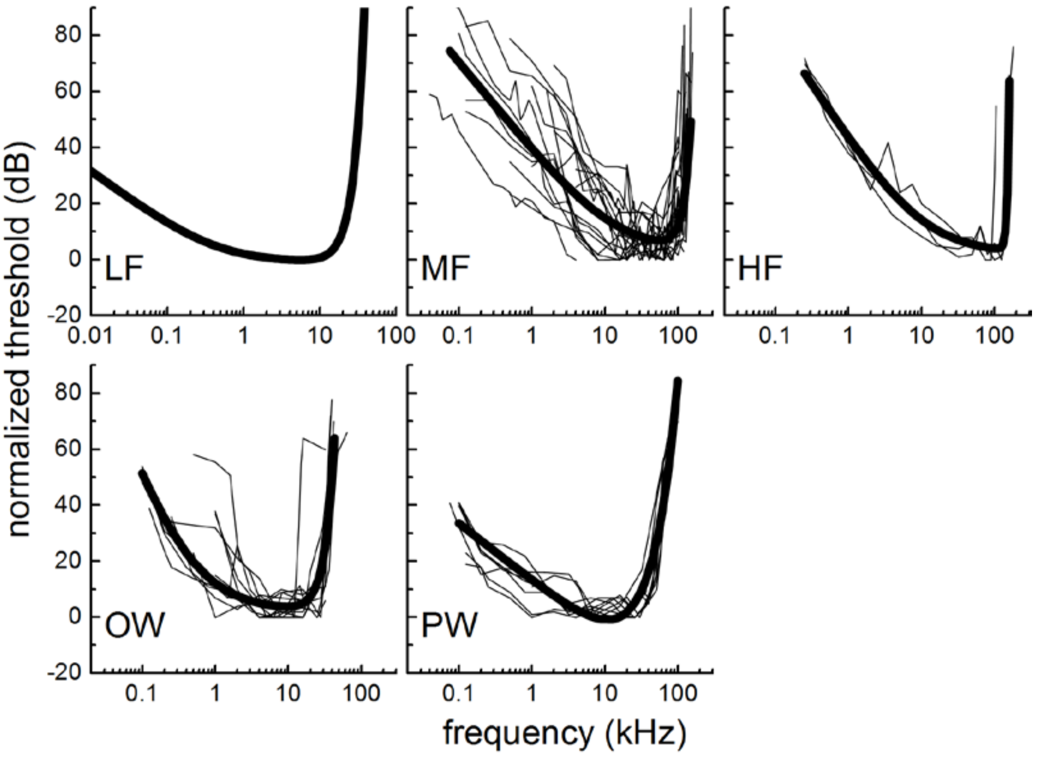

Figure 4: **Resulting normalized composite audiograms for low-frequency (LF), mid-frequency (MF), and high-frequency (HF) cetaceans and phocid (PW) and otariid (OW) pinnipeds (from Finneran 2016). For resulting original composite audiogram, see Appendix A, Figure A5.**

Table 2: Summary of data available for deriving composite audiograms.[†]

Hearing Group	Species (number of individuals)	References
Mid-Frequency (MF) Cetaceans	Beluga (9)	White et al. 1978; Awbrey et al. 1988; Johnson et al. 1989; Ridgway et al. 2001; Finneran et al. 2005b
	Bottlenose dolphin (6)	Johnson 1967; Ljungblad et al. 1982; Lemonds 1999; Brill et al. 2001;Schlundt et al. 2008; Finneran et al. 2010a
	False killer whale (1)	Thomas et al. 1988
	Killer whale (8)	Szymanski et al. 1999; Branstetter et al. 2017[+]
	Risso's dolphin (1)	Nachtigall et al. 1995
	Pacific white-sided dolphin (1)	Tremel et al. 1996
	Striped dolphin (1)	Kastelein et al. 2003
	Tucuxi (1)	Sauerland and Dehnhardt 1998
High-Frequency (HF) Cetaceans	Amazon River dolphin (1)	Jacobs and Hall 1972
	Harbor porpoise (5)	Kastelein et al. 2010; Kastelein et al. 2015c; Kastelein et al. 2017a[+]
Phocid Pinnipeds (PW) Underwater	Harbor seal (4)	Terhune 1988; Kastelein et al. 2009b; Reichmuth et al. 2013
	Northern elephant seal (1)	Kastak and Schusterman 1999
	Ringed seal (1)	Sills et al. 2015
	Spotted seal (2)	Sills et al. 2014
Otariid Pinnipeds* (OW) Underwater	California sea lion (4)	Mulsow et al. 2012; Reichmuth and Southall 2012; Reichmuth et al. 2013
	Northern fur seal (3)	Moore and Schusterman 1987; Babushina et al. 1991
	Steller sea lion (2)	Kastelein et al. 2005a

[†] More details on individual subjects are available in Appendix A (Table A2). Some datasets were excluded due to subjects having high-frequency hearing loss or aberrant audiograms. These included subjects from: Møhl 1968; Andersen 1970; Hall and Johnson 1972; Terhune and Ronald 1972; Terhune and Ronald 1975; Thomas et al. 1990; Wang et al. 1992; Babushina 1997; Kastak et al. 2002; Finneran et al. 2005 (Turner); Yuen et al. 2005; Finneran et al. 2007a; Sills et al. 2015 (Natchek). Decisions to exclude data were based on comparison of the individual published audiograms and ambient noise characteristics to those for other individuals of the same or closely related species. The most common reasons for excluding an individual's data were abnormal audiograms featuring high-frequency hearing loss (typically seen in older animals) or "notches" in the audiogram, or data collected in the presence of relatively high ambient noise that resulted in elevated thresholds. Excluding these data ensured that the composite audiograms were not artificially elevated, which could result in unrealistically high thresholds.

+Two publications with behavioral audiograms became available after the Technical Guidance's finalization in 2016. However, upon consideration of these two studies during EO 13795 review of the Technical Guidance, including recommendations from other Federal agencies, NMFS determined it is not practical from an implementation standpoint to add these studies at this time. NMFS will include these studies in the next revision of this document (i.e., Version 3.0). For more detail on these studies, see Section III.

* The otariid pinniped (underwater) hearing group's composite audiogram contains data from a single Pacific walrus (*Odobenus rosmarus*) from Kastelein et al. 2002 and a single sea otter (*Enhydra lutris nereis*) from Ghoul and Reichmuth 2014, which are species under the jurisdiction of the USFWS. However, since marine mammal audiogram data are limited, a decision was made to include all available datasets from in-water groups to derive composite audiograms for this hearing group. For frequencies below 30 kHz, the difference in the composite audiogram with and without these data are < 2 dB. For comparison, see Appendix A, Figure A4.

In deriving marine mammal composite audiograms, NMFS established an informal data hierarchy in terms of assessing these types of data. Specifically, audiograms obtained via behavioral methodologies were determined to provide the most representative (sensitive) presentation of hearing ability (Finneran et al. 2007a), followed by auditory evoked potential (AEP) data,[19] and lastly by mathematical/anatomical models for species where no data are available (i.e., LF cetaceans). Thus, the highest quality data available for a specific hearing group were used.[20]

For LF cetaceans, only two studies were available for consideration (i.e., predicted audiogram for a humpback whale from Houser et al. 2001 and fin whale from Cranford and Krysl 2015), which alone was not enough to derive a predicted audiogram for this entire hearing group. Thus, an alternative approach was used to derive a composite audiogram[21] and associated auditory weighting function for LF cetaceans (i.e., composite audiogram parameters had to be predicted; For specifics, on this process, see Appendix A_1).

2. The low-frequency exponent (a) was defined using the smaller of the low-frequency slope from either the composite audiogram or the lower-frequency slope of the equal latency contours (if available) and then divided by twenty ($s_0/20$). This results in the slope matching the shallower slope of the audiogram.

3. The high-frequency exponent (b) was set equal to two to match the previously derived marine mammal auditory weighting functions from Finneran and Jenkins (2012), since no new TTS measurements were available at higher frequencies and equal latency data at these frequencies are considered highly variable.

4. Low- (f_1) and high-frequency cutoffs (f_2) were defined as the frequencies below and above the frequency of best hearing (f_0) from original data, where the threshold values were ΔT above the threshold at f_0 . These two parameters reflect the hearing group’s most susceptible frequency range.

5. To determine ΔT, the auditory exposure function amplitude was calculated for MF and HF cetaceans examining ΔT values ranging from zero to 20 dB. Then, the K gain parameter was adjusted to minimize the mean-squared error (MSE) between the function amplitude (original and normalized composite audiograms) and MF and HF cetacean TTS data. The value of ΔT resulting the lowest MSE was eleven for both the normalized and original data. This value was used for other hearing groups.

6. Hearing groups where TTS data are available (i.e., MF and HF cetaceans and PW and OW pinniped) were used to define K (Step 4 above). For LF cetaceans, where data were

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[19] Despite not directly including AEP audiograms in the development of a hearing groups’ composite audiogram, these date were evaluated to ensure species were placed within the appropriate hearing group and to ensure a species where only AEP data are available were within the bounds of the composite audiogram for that hearing group. Furthermore, AEP TTS data are presented within the Technical Guidance for comparative purposes alongside TTS data collected by behavioral methods illustrating that the AEP TTS data are within the bounds (the majority of the time above) of those collected by behavioral methods.

[20] Behavioral techniques for obtaining audiograms measure perception of sound by a receiver, while AEP methods measure only neural activity (Jewett and Williston 1971) (i.e., two methodologies are not necessarily equivalent). As a result, behavioral techniques consistently produce lower thresholds than those obtained by AEPs (e.g., Szymanski et al. 1999; Yuen et al. 2005; Houser and Finneran 2006). Currently, there are no means established for “correcting” AEP data so that it may be more comparable to those obtained via behavioral methods (Heffner and Heffner 2003; Finneran 2015; Sisneros et al. 2016; Erbe et al. 2016).

[21] During the third public comment period on the Technical Guidance in March 2016, ambient noise levels from Clark and Ellison 2004 were offered by a group of subject matter experts as additional scientific support to NMFS’ LF cetacean weighting function (for direct comparison to NOAA’s 2016 LF cetacean weighting function see: Public comment made via Regulations.gov).

not available, TTS onset was estimated by assuming the numeric difference between auditory threshold (Figure 4, original data) and TTS onset at the frequency of best hearing (f_0) would be similar across hearing groups. For LF cetaceans auditory threshold had to be predicted, since no data exist (For specifics on methodology, see Appendix A, Table A7).

7. The weighting function parameter (*C*) was determined by substituting parameters a, b, f_1, and f_2 in Equation 1 and setting the peak amplitude of the function to zero.

For each hearing group, the resulting numeric values associated with these parameters and resulting weighted TTS onset threshold for non-impulsive sources (weighted $\mathrm{SEL_{cum}}$ metric) are listed in Table 3 and resulting auditory weighting functions are depicted in Figures 1 and 2.

Table 3: Summary of auditory weighting and exposure function parameters.

Hearing Group	a	b	f_1 (kHz)	f_2 (kHz)	C (dB)	K (dB)	Weighted TTS onset threshold* ($\mathrm{SEL_{cum}}$)
Low-frequency (LF) cetaceans	1.0	2	0.2	19	0.13	179	179 dB
Mid-frequency (MF) cetaceans	1.6	2	8.8	110	1.20	177	178 dB
High-frequency (HF) cetaceans	1.8	2	12	140	1.36	152	153 dB
Phocid pinnipeds (PW) (underwater)	1.0	2	1.9	30	0.75	180	181 dB
Otariid pinnipeds (OW) (underwater)	2.0	2	0.94	25	0.64	198	199 dB

* Determined from minimum value of auditory exposure function and the weighting function at its peak (i.e., mathematically equivalent to $K + C$).

Note: Appendix A, Figure A17 illustrates that the resulting auditory exposure functions (and subsequent weighting functions) are broader than the composite audiograms or audiogram from an individual species. This is important to note because the auditory weighting/exposure functions are derived not just from data associated with the composite audiogram but also account for available TTS onset data.

2.2.4 Application of Marine Mammal Auditory Weighting Functions for PTS Onset Thresholds

The application of marine mammal auditory weighting functions emphasizes the importance of making measurements and characterizing sound sources in terms of their overlap with biologically-important frequencies (e.g., frequencies used for environmental awareness, communication or the detection of predators or prey), and not only the frequencies of interest or concern for the completion of the sound-producing activity (i.e., context of sound source).

If the frequencies produced by a sound source are outside a hearing group's most susceptible hearing range (where the auditory weighting function amplitude is 0), sounds at those frequencies are required to have a higher sound pressure level to produce a similar threshold shift (i.e., PTS onset) as sounds with frequencies in the hearing group's most susceptible hearing range. Because auditory weighting functions take into account a hearing group's differing susceptibility to frequencies, the implementation of these functions typically results in smaller isopleths[22] for

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[22] Note: Thresholds associated with a hearing group do not change depending on how much a sound may overlap a group's most susceptible frequency range. Instead, weighting functions affect exposure modeling/analysis via the resulting size of the isopleth (area) associated with the threshold based on how susceptible that particular hearing group

frequencies where the group is less susceptible. Additionally, if the sound source produces frequencies completely outside the generalized hearing range of a given hearing group (i.e., has no harmonics/subharmonics that are capable of producing sound within the hearing range of a hearing group), then the likelihood of the sound causing hearing loss is considered low.[23]

Marine mammal auditory weighting functions are used in conjunction with corresponding weighted SEL_{cum} PTS onset thresholds. If the use of the full auditory weighting function is not possible by an action proponent (i.e., consider auditory weighting function over multiple frequencies for broadband source), NMFS has provided an alternative tool based on a simpler auditory weighting function (See Appendix D).

Tougaard et al. (2015) reviewed the impacts of using auditory weighting functions and various considerations when applying them during the data evaluation and implementation stages (e.g., consequences of using too broad or too narrow of a filter) and suggested some modifications (correction factors) to account for these considerations. However, there are no data to support doing so (i.e., selection would be arbitrary). Moreover, various conservative factors have been accounted for in the development of auditory weighting functions and thresholds: A 6 dB threshold shift was used to represent TTS onset; the methodology does not incorporate exposures where TTS did not occur; and the potential for recovery is not accounted for. Additionally, the means by which NMFS is applying auditory weighting functions is supported and consistent with what has been done for humans (i.e., A-weighted thresholds used in conjunction with A-weighting during implementation).

2.2.4.1 Measuring and Maintaining Full Spectrum for Future Analysis

It is recommended marine mammal auditory weighting functions be applied after sound field measurements[24] have been obtained (i.e., post-processing; it is recommended that auditory weighting functions not be applied beforehand), with the total spectrum of sound preserved for later analysis (i.e., if auditory weighting functions are updated or if there is interest in additional species, then data can still be used). Additionally, it is important to consider measurements that encompass the entire frequency band that a sound source may be capable of producing (i.e., sources often produce sounds, like harmonics/subharmonics, beyond the frequency/band of interest; e.g., Deng et al. 2014; Hastie et al. 2014).

2.3 PTS ONSET THRESHOLDS

Available data from humans and other terrestrial mammals indicate that a 40 dB threshold shift approximates PTS onset (see Ward et al. 1958; Ward et al. 1959; Ward 1960; Kryter et al. 1966; Miller 1974; Ahroon et al. 1996; Henderson et al. 2008). Southall et al. (2007) also recommended this definition of PTS onset.

PTS onset thresholds for marine mammals have not been directly measured and are extrapolated from available TTS onset measurements. Thus, based on cetacean measurements from TTS

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is to the sound being modeled. For example, a hearing group could have different size isopleths associated with the same threshold, if one sound was within its most susceptible frequency range and the other was not (i.e., sound in most susceptible hearing range will result in larger isopleth compared to sound outside the most susceptible hearing range).

[23] The potential for sound to damage beyond the level the ear can perceive exists (Akay 1978), which is why the thresholds also include the PK metric, which are flat or unweighted within the generalized hearing range of a hearing group.

[24] Note: Sound field measurements refers to actual field measurements, which are not a requirement of this Technical Guidance, and not to exposure modeling analyses, where it may be impractical due to data storage and cataloging restraints.

studies (see Southall et al. 2007; Finneran 2015; Finneran 2016 found in Appendix A of this Technical Guidance) a threshold shift of 6 dB is considered the minimum threshold shift clearly larger than any day-to-day or session-to-session variation[25] in a subject's normal hearing ability and is typically the minimum amount of threshold shift that can be differentiated in most experimental conditions (Finneran et al. 2000; Schlundt et al. 2000; Finneran et al. 2002). Thus, NMFS has set the onset of TTS at the lowest level that exceeds recorded variation (i.e., 6 dB).

There are different mechanisms (e.g., anatomical, neurophysiological) associated with TTS vs. PTS onset, making the relationship between these types of TSs not completely direct. Nevertheless, the only data available for marine mammals, currently and likely in the future, will be from TTS studies (i.e., unlike for terrestrial mammals where direct measurements of PTS exist). Thus, TTS represents the best information available from which PTS onset can be estimated.

The thresholds presented in Table 4 consist of both an acoustic threshold and auditory weighting function for the SEL_{cum} metric (auditory weighting functions are considered not appropriate for PK metric).

NMFS recognizes that the implementation of marine mammal auditory weighting functions represents a new factor for consideration that may exceed the capabilities of some action proponents. Thus, NMFS has developed alternative tools for those who cannot fully apply auditory weighting functions associated with the weighted SEL_{cum} metric (See Appendix D).

2.3.1 Impulsive and Non-Impulsive Source Thresholds

This Technical Guidance divides sources into impulsive and non-impulsive based on physical characteristics at the source, with impulsive sound having physical characteristics making them more injurious[26] (e.g., high peak sound pressures and rapid rise times) than non-impulsive sound sources (terrestrial mammal data: Buck et al. 1984; Dunn et al. 1991; Hamernik et al. 1993; Clifford and Rogers 2009; marine mammal data: reviewed in Southall et al. 2007 and Finneran 2016 that appears as Appendix A of this Technical Guidance).

The characteristics of the sound at a receiver, rather than at the source, are the relevant consideration for determining potential impacts. However, understanding these physical characteristics in a dynamic system with receivers moving over space and time is difficult. Nevertheless, it is known that as sound propagates from the source the characteristics of impulsive sounds that make them more injurious start to dissipate due to effects of propagation (e.g., time dispersion/time spreading; Urick 1983; Sertlek et al. 2014).

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[25] Similarly, for humans, NIOSH (1998) regards the range of audiometric testing variability to be approximately 5 dB.

[26] Exposure to impulsive sounds more often lead to mechanical damage of the inner ear, as well as more complex patterns of hearing recovery (e.g., Henderson and Hamernik 1986; Hamernik and Hsueh 1991).

Table 4: Summary of PTS onset thresholds.

	PTS Onset Thresholds* (Received Level)	
Hearing Group	**Impulsive**	**Non-impulsive**
Low-Frequency (LF) Cetaceans	*Cell 1* $L_{\text{pk,flat}}$: 219 dB $L_{\text{E,LF,24h}}$: 183 dB	*Cell 2* $L_{\text{E,LF,24h}}$: 199 dB
Mid-Frequency (MF) Cetaceans	*Cell 3* $L_{\text{pk,flat}}$: 230 dB $L_{\text{E,MF,24h}}$: 185 dB	*Cell 4* $L_{\text{E,MF,24h}}$: 198 dB
High-Frequency (HF) Cetaceans	*Cell 5* $L_{\text{pk,flat}}$: 202 dB $L_{\text{E,HF,24h}}$: 155 dB	*Cell 6* $L_{\text{E,HF,24h}}$: 173 dB
Phocid Pinnipeds (PW) (Underwater)	*Cell 7* $L_{\text{pk,flat}}$: 218 dB $L_{\text{E,PW,24h}}$: 185 dB	*Cell 8* $L_{\text{E,PW,24h}}$: 201 dB
Otariid Pinnipeds (OW) (Underwater)	*Cell 9* $L_{\text{pk,flat}}$: 232 dB $L_{\text{E,OW,24h}}$: 203 dB	*Cell 10* $L_{\text{E,OW,24h}}$: 219 dB

* Dual metric thresholds for impulsive sounds: Use whichever results in the largest isopleth for calculating PTS onset. If a non-impulsive sound has the potential of exceeding the peak sound pressure level thresholds associated with impulsive sounds, these thresholds are recommended for consideration.

Note: Peak sound pressure level ($L_{p,\text{0-pk}}$) has a reference value of 1 µPa, and weighted cumulative sound exposure level ($L_{\text{E},p}$) has a reference value of $1\mu\text{Pa}^2\text{s}$. In this Table, thresholds are abbreviated to be more reflective of International Organization for Standardization standards (ISO 2017). The subscript “flat” is being included to indicate peak sound pressure are flat weighted or unweighted within the generalized hearing range of marine mammals (i.e., 7 Hz to 160 kHz). The subscript associated with weighted cumulative sound exposure level thresholds indicates the designated marine mammal auditory weighting function (LF, MF, and HF cetaceans, and PW and OW pinnipeds) and that the recommended accumulation period is 24 hours. The cumulative sound exposure level thresholds could be exceeded in a multitude of ways (i.e., varying exposure levels and durations, duty cycle). When possible, it is valuable for action proponents to indicate the conditions under which these thresholds will be exceeded.

For the purposes of this Technical Guidance,[27] sources are divided and defined as the following:

- Impulsive: produce sounds that are typically transient, brief (less than 1 second), broadband, and consist of high peak sound pressure with rapid rise time and rapid decay (ANSI 1986; NIOSH 1998; ANSI 2005).

- Non-impulsive: produce sounds that can be broadband, narrowband or tonal, brief or prolonged, continuous or intermittent) and typically do not have a high peak sound pressure with rapid rise/decay time that impulsive sounds do (ANSI 1995; NIOSH 1998).

Note: The term “impulsive” in this document relates specifically to NIHL and specifies the physical characteristics of an impulsive sound source, which likely gives them a higher potential to cause auditory TTS/PTS. This definition captures how these sound types may be more likely to affect auditory physiology and is not meant to reflect categorizations associated with behavioral disturbance.

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[27] If there is unclear, consider the most applicable definition and consult with NMFS.

2.3.2 Metrics

2.3.2.1 Weighted Cumulative Sound Exposure Level (SEL_{cum}) Metric

The weighted SELcum metric takes into account both received level and duration of exposure (ANSI 2013), both factors that contribute to NIHL. Often this metric is normalized to a single sound exposure of one second. NMFS intends for the weighted SELcum metric to account for the accumulated exposure (i.e., weighted SELcum cumulative exposure over the duration of the activity within a 24-h period).

The recommended application of the weighted SEL_{cum} metric is for individual activities/sources. It is not intended for accumulating sound exposure from multiple activities occurring within the same area or over the same time or to estimate the impacts of those exposures to an animal occurring over various spatial or temporal scales. Current data available for deriving thresholds using this metric are based on exposure to only a single source and may not be appropriate for situations where exposure to multiple sources is occurring. As more data become available, the use of this metric can be re-evaluated, in terms of appropriateness, for application of exposure from multiple activities occurring in space and time.

Equal Energy Hypothesis

One assumption made when applying the weighted SEL_{cum} metric is the equal energy hypothesis (EEH), where it is assumed that sounds of equal SEL_{cum} produce an equal risk for hearing loss (i.e., if the weighted SEL_{cum} of two sources are similar, a sound from a lower level source with a longer exposure duration may have similar risks to a shorter duration exposure from a higher level source). As has been shown to be the case with humans and terrestrial mammals (Henderson et al. 1991), the EEH does not always accurately describe all exposure situations for marine mammals due the inherent complexity of predicting TSs (e.g., Kastak et al. 2007; Mooney et al. 2009a; Mooney et al. 2009b; Finneran et al. 2010a; Finneran et al. 2010b; Finneran and Schlundt 2010; Kastelein et al. 2012b; Kastelein et al. 2013b; Kastelein et al. 2014a; Popov et al. 2014).

Factors like sound level (e.g., overall level, sensation level, or level above background), duration, duty cycle (intermittent versus continuous exposure; potential recovery between intermittent periods), number of transient components (short duration and high amplitude), and/or frequency (especially in relation to hearing sensitivity) often are also important factors associated with TSs (e.g., Buck et al. 1984; Clark et al. 1987; Ward 1991; Lataye and Campo 1996). This is especially the case for exposure to impulsive sound sources (Danielson et al. 1991; Henderson et al. 1991; Hamernik et al. 2003), which is why thresholds in this Technical Guidance are also expressed as a PK metric (see next section). However, in many cases the EEH approach functions reasonably well as a first-order approximation, especially for higher-level, short-duration sound exposures such as those that are most likely to result in TTS in marine mammals[28] (Finneran 2015). Additionally, no currently supported alternative method to accumulate exposure is available. If alternative methods become available, they can be evaluated and considered when the Technical Guidance is updated.

Recommended Accumulation Period

To apply the weighted SEL_{cum} metric, a specified accumulation period is needed. Generally, it is predicted that most receivers will minimize the amount of time they remain in the closest ranges to a sound source/activity. Exposures at the closest point of approach are the primary exposures contributing to a receiver's accumulated level (Gedamke et al. 2011). Additionally, several

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[28] When possible, it is valuable for action proponents to indicate the exposure conditions under which these thresholds are likely to be exceeded.

important factors determine the likelihood and duration a receiver is expected to be in close proximity to a sound source (i.e., overlap in space and time between the source and receiver). For example, accumulation time for fast moving (relative to the receiver) mobile sources is driven primarily by the characteristics of source (i.e., speed, duty cycle). Conversely, for stationary sources, accumulation time is driven primarily by the characteristics of the receiver (i.e., swim speed and whether transient or resident to the area where the activity is occurring). NMFS recommends a maximum baseline accumulation period of 24 hours, but acknowledges that there may be specific exposure situations where this accumulation period requires adjustment (e.g., if activity lasts less than 24 hours or for situations where receivers are predicted to experience unusually long exposure durations[29]).

After sound exposure ceases or between successive sound exposures, the potential for recovery from hearing loss exists, with PTS resulting in incomplete recovery and TTS resulting in complete recovery. Predicting recovery from sound exposure can be quite complicated. Currently, recovery in wild marine mammals cannot be accurately quantified. However, Finneran et al. (2010a) and Finneran and Schlundt (2013) proposed a model that approximates recovery in bottlenose dolphins and whose applicability to other species and other exposure conditions has yet to be determined. In the development of the Technical Guidance's thresholds, NMFS assumes for intermittent, repeated exposure that there is no recovery between subsequent exposures, although it has been demonstrated in terrestrial mammals (Clark et al. 1987; Ward 1991) and more recently in a marine mammal studies (Finneran et al. 2010b; Kastelein et al. 2014a; Kastelein et al. 2015b), that there is a reduction in damage and hearing loss with intermittent exposures.

Existing NMFS thresholds have only accounted for proximity of the sound source to the receiver, but thresholds in this Technical Guidance (i.e., expressed as weighted SEL_{cum}) now take into account the duration, as well as level of exposure. NMFS recognizes that accounting for duration of exposure, although supported by the scientific literature, adds a new factor, as far as application of this metric to real-world activities and that not all action proponents may have the ability to easily apply this additional component.

NMFS does not provide specifications necessary to perform exposure modeling and relies on the action proponent to determine the model that best represents their activity. However, NMFS acknowledges that different action proponents may have different capabilities and levels of modeling sophistication. NMFS has provided a simple means of approximating exposure for action proponents that are unable to apply various factors into their model (See Appendix D).

NMFS will convene a working group to investigate means for deriving more realistic accumulation periods, especially for stationary sources (anticipated in 2018).

2.3.2.2 Peak Sound Pressure Level (PK) Metric[30]

Sound exposure containing transient components (e.g., short duration and high amplitude; impulsive sounds) can create a greater risk of causing direct mechanical fatigue to the inner ear (as opposed to strictly metabolic) compared to sounds that are strictly non-impulsive (Henderson and Hamernik 1986; Levine et al. 1998; Henderson et al. 2008). Often the risk of damage from these transients does not depend on the duration of exposure. This is the concept of "critical level," where damage switches from being primarily metabolic to more mechanical and short

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[29] For example, where a resident population could be found in a small and/or confined area (Ferguson et al. 2015) and/or exposed to a long-duration activity with a large sound source, or where a continuous stationery activity is nearby an area where marine mammals congregate, like a pinniped pupping beach.

[30] Note: Do not confuse peak sound pressure level with *maximum* root mean square sound pressure level.

duration of impulse can be less than the ear's integration time, leading to the potential to damage beyond the level the ear can perceive (Akay 1978).

Human noise standards recognize and provide separate thresholds for impulsive sound sources using the PK metric (Occupational Safety and Health Administration (OSHA) 29 CFR 1910.95; Starck et al. 2003). Thus, weighted SEL_{cum} is not an appropriate metric to capture all the effects of impulsive sounds (i.e., often violates EEH; NIOSH 1998), which is why instantaneous PK level has also been chosen as part of NMFS' dual metric thresholds for impulsive sounds.[31] Auditory weighting is not considered appropriate with the PK metric, as direct mechanical damage associated with sounds having high peak sound pressures typically does not strictly reflect the frequencies an individual species hears best (Ward 1962; Saunders et al. 1985; ANSI 1986; DOD 2004; OSHA 29 CFR 1910.95). Thus, this Technical Guidance recommends that the PK thresholds be considered unweighted/flat-weighted within the generalized hearing range of marine mammals (i.e., 7 Hz to 160 kHz).

2.3.2.3 Comparison Among Metrics

NMFS' existing thresholds were expressed as root-mean-square sound pressure level (RMS SPL), which is a different metric from the PK and weighted SEL_{cum} that are being recommended for the PTS onset thresholds in this Technical Guidance. Thus, NMFS recommends caution when comparing prior thresholds to those presented in this document (i.e., metrics are not directly comparable). For example, a RMS SPL threshold of 180 dB is not equal to a PK threshold of 180 dB. Further, the weighted SEL_{cum} metric incorporates exposure duration and is an energy level with a different reference value (re: $1\mu Pa^2$-s). Thus, it is not directly comparable to other metrics that describe sound pressure levels (re: 1 µPa)[32].

2.3.3 Development of PTS Onset Thresholds

The development of the PTS onset thresholds consisted of the following procedure described in Finneran 2016 (Appendix A[33]):

1. Identification of available data on marine mammal hearing and noise-induced hearing loss (e.g., Southall et al. 2007; Finneran 2015; Finneran 2016 references listed in available reports/publications).

2. Methodology to derive marine mammal auditory weighting functions (described in more detail in Section 2.2.3 and Appendix A).

3. Evaluation and summary of currently available published data (32 studies found in Table 5) on hearing loss associated with sound exposure in marine mammals.
    - Because no published measurements exist on PTS in marine mammals, TTS onset measurements and associated thresholds were evaluated and summarized to extrapolate to PTS onset thresholds.

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[31] For non-impulsive sounds, the weighted SEL_{cum} threshold will likely to result in the largest isopleth, compared to the PK threshold. Thus, for the majority of non-impulsive sounds, the consideration of the PK threshold is unnecessary. However, if a non-impulsive sound has the potential of exceeding the PK threshold associated with impulsive sounds, NMFS recommends these thresholds be considered (i.e., dual metrics).

Publications on how to estimate PK from SEL for seismic airguns and offshore impact pile drivers may be useful to action proponents (Galindo-Romero et al. 2015; Lippert et al. 2015).

[32] For more information and illustrations on metrics, see: Discovery of Sound in the Sea.

[33] Wright 2015 provides a critique of this methodology. For NMFS' response to this critique, see the Federal Register notice associated with the finalized Technical Guidance, specifically the section responding to public comments.

- Studies divided into the following categories:
    - o Temporal Characteristics: Impulsive and Non-impulsive

    - o Marine Mammal Hearing Groups: LF Cetaceans, MF Cetaceans, HF Cetaceans, PW Pinnipeds, and OW Pinniped

4. Determination of TTS onset threshold by individual (RLs, in both PK and SEL_{cum} metrics) based on methodology from Finneran 2016 for impulsive and non-impulsive sounds (Full detail in Appendix A).
    - <u>Non-impulsive sounds</u>:
        - o Only TTS data from behavioral studies were used, since studies using AEP methodology typically result in larger thresholds shifts (e.g., up to 10 dB difference, Finneran et al. 2007a) and are considered to be non-representative (as illustrated in Appendix A, Figure A9)

Table 5: Available underwater marine mammal threshold shift studies.

References in Chronologic Order$^+$	Sound Source (Sound Source Category)	Species (number of individuals^)
Kastak et al. 1999	Octave-band noise (non-impulsive)	California sea lion (1); northern elephant seal (1); harbor seal (1)
Finneran et al. 2000	Explosion simulator (impulsive)*****	Bottlenose dolphin (2); beluga (1)
Schlundt et al. 2000	Tones (non-impulsive)	Bottlenose dolphin (5); beluga (2)
Finneran et al. 2002	Seismic watergun (impulsive)	Bottlenose dolphin (1); beluga (1)
Finneran et al. 2003	Arc-gap transducer (impulsive)*****	California sea lion (2)
Nachtigall et al. 2003	Octave-band noise (non-impulsive)	Bottlenose dolphin (1)
Nachtigall et al. 2004	Octave-band noise (non-impulsive)	Bottlenose dolphin (1)
Finneran et al. 2005a	Tones (non-impulsive)	Bottlenose dolphin (2)
Kastak et al. 2005	Octave-band noise (non-impulsive)	California sea lion (1); northern elephant seal (1); harbor seal (1)
Finneran et al. 2007a	Tones (non-impulsive)	Bottlenose dolphin (1)
Lucke et al. 2009	Single airgun (impulsive)	Harbor porpoise (1)
Mooney et al. 2009a	Octave-band noise (non-impulsive)	Bottlenose dolphin (1)
Mooney et al. 2009b	Mid-frequency sonar (non-impulsive)	Bottlenose dolphin (1)
Finneran et al. 2010a	Tones (non-impulsive)	Bottlenose dolphin (2)
Finneran et al. 2010b	Tones (non-impulsive)	Bottlenose dolphin (1)
Finneran and Schlundt 2010	Tones (non-impulsive)	Bottlenose dolphin (1)
Popov et al. 2011a	½ octave band noise (non-impulsive)	Yangtze finless porpoise (2)
Popov et al. 2011b	½ octave band noise (non-impulsive)	Beluga (1)
Kastelein et al. 2012a	Octave-band noise (non-impulsive)	Harbor seal (2)
Kastelein et al. 2012b	Octave-band noise (non-impulsive)	Harbor porpoise (1)
Finneran and Schlundt 2013	Tones (non-impulsive)	Bottlenose dolphin (2)
Popov et al. 2013	½ -octave band noise (non-impulsive)	Beluga (2)
Kastelein et al. 2013a	Octave-band noise (non-impulsive)	Harbor seal (1)
Kastelein et al. 2013b	Tone (non-impulsive)	Harbor porpoise (1)
Popov et al. 2014	½ octave band noise (non-impulsive)	Beluga (2)
Kastelein et al. 2014a	1-2 kHz sonar (non-impulsive)	Harbor porpoise (1)
Kastelein et al. 2014b	6.5 kHz tone (non-impulsive)	Harbor porpoise (1)
Kastelein et al. 2015a	Impact pile driving (impulsive)	Harbor porpoise (1)
Kastelein et al. 2015b	6-7 kHz sweeps (non-impulsive)	Harbor porpoise (1)
Finneran et al. 2015	Single airgun producing multiple shots (impulsive)*****	Bottlenose dolphin (3)
Popov et al. 2015	½ octave band noise (non-impulsive)	Beluga (1)
Kastelein et al. 2016	Impact pile driving (impulsive)*****	Harbor porpoise (2)
Reichmuth et al. 2016	Single airgun (impulsive) *****	Ringed seals (2); Spotted seals (2)
Popov et al. 2017	½ octave band noise (non-impulsive)	Beluga (1)
Kastelein et al. 2017b	Simultaneous airguns producing multiple shots (impulsive)	Harbor porpoise (1)
Kastelein et al. 2017c	3.5-4.1 kHz sonar (non-impulsive)	Harbor porpoise (2)

^Note: Some individuals have been used in multiple studies.

*****No incidents of temporary threshold shift were recorded in study.

- o TTS onset derived on a per individual basis by combining available data to create single TTS growth curve (e.g., dB TTS/dB noise) by frequency as a function of SEL_{cum}.

- o TTS onset was defined as the SEL_{cum} value from the growth curve interpolated at a value of TTS = 6 dB. Only datasets where data were available with a threshold shift (TS) above and below 6 dB were used to define TTS onset (i.e., extrapolation was not performed on datasets not meeting this criterion).

- o Interpolation was used to estimate SEL_{cum} necessary to induce 6 dB of TTS by hearing group (Appendix A, Figures A10-A13). Note: Appendix A, Figures A18-A20 illustrate available marine mammal TTS data in relation to the composite audiogram and auditory exposure function.

- o Finally, weighted thresholds for TTS onset were determined by the minimum value of the auditory exposure function (Equation 2), which is mathematically equivalent to $K + C$ (Table 6).

Table 6: TTS onset thresholds for non-impulsive sounds.

Hearing Group	K (dB)	C (dB)	Weighted TTS onset acoustic threshold (SEL_{cum})
Low-frequency (LF) cetaceans	179	0.13	179 dB
Mid-frequency (MF) cetaceans	177	1.20	178 dB
High-frequency (HF) cetaceans	152	1.36	153 dB
Phocid pinnipeds (underwater)	180	0.75	181 dB
Otariid pinnipeds (underwater)	198	0.64	199 dB

- Impulsive sounds:
  - o Available TTS data for impulsive sources were weighted based on auditory weighting functions for the appropriate hearing group (MF and HF cetaceans only from two studies: Finneran et al. 2002; Lucke et al. 2009).

  - o For hearing groups, where impulsive TTS onset data did not exist (LF cetaceans and PW and OW pinnipeds), Finneran (2015) derived impulsive TTS onset thresholds using the relationship between non-impulsive TTS onset thresholds and impulsive TTS onset thresholds for MF and HF cetaceans (i.e., similar to what was presented in Southall et al. 2007). Using the mean/median of these data resulted in an 11 dB relationship, which was used as a surrogate for the other hearing groups (i.e., non-impulsive TTS threshold was 11 dB higher than impulsive TTS threshold).

  - o A similar approach was investigated for the PK threshold, resulting in a 45 dB relationship, which was considered unrealistic (approaching cavitation level of water; Southall et al. 2007). Upon further consideration, the auditory system's dynamic range was determined a more appropriate methodology for estimating PK sound pressure thresholds.[34]

    The dynamic range methodology assumes that the PK TTS onset acoustic threshold for MF and HF cetaceans defines the upper end of

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[34] Dynamic range is used in human noise standards to define the PK acoustic threshold for impulsive sounds (e.g., 140 dB from OSHA 29 CFR 1910.95). For the purposes of this Technical Guidance, the intent is to relate the threshold of audibility and TTS onset level, not the threshold of pain, as dynamic range is typically defined (Yost 2007).

those hearing groups' dynamic range (i.e., PK threshold: 224 dB for MF cetaceans and PK threshold: 196 dB for HF cetaceans), with the threshold of audibility derived from the frequency of best hearing (f_0) from the composite audiogram (i.e., 54 dB for MF cetaceans and 48 dB for HF cetaceans) defining the lower end of the groups' dynamic range.

This results in a dynamic range of 170 dB for MF cetaceans and 148 dB for HF cetaceans. The median/mean dynamic range from these two hearing groups (i.e., 159 dB) is used as the surrogate dynamic range for LF cetaceans (best hearing at f_0= 54 dB; Resulting in a PK TTS threshold of 213 dB); PW pinnipeds (best hearing at f_0=53 dB; Resulting in a PK TTS threshold of 212 dB); and OW pinnipeds (best hearing at f_0 =67 dB; Resulting in a PK TTS threshold of 226 dB).

5. Extrapolation for PTS onset threshold (in both PK and SEL metrics) based on data from humans and terrestrial mammals, with the assumption that the mechanisms associated with noise-induced TS in marine mammals is similar, if not identical, to that recorded in terrestrial mammals.

    - <u>Non-impulsive sounds</u>:
        - PTS onset thresholds were estimated using TTS growth rates based on those marine mammal studies where 20 dB or more of a TS was induced. This was done to estimate more accurately PTS onset, since using growth rates based on smaller TSs are often shallower than compared to those inducing greater TSs (See Appendix A, Figures A10-A13).

        - PTS onset was derived using the same methodology as TTS onset, with PTS onset defined as the $\mathrm{SEL}_{\mathrm{cum}}$ value from the fitted curve at a TTS of 40 dB.

        - Offset between TTS and PTS onset thresholds were examined and ranged from 13 to 37 dB (mean/median: 25/25 dB for cetacean data). Thus, based on these data, a conservative 20 dB offset was chosen to estimate PTS onset thresholds from TTS onset thresholds for non-impulsive sources (i.e., 20 dB was added to K to determine PTS onset, assuming the shape of the PTS auditory exposure function is identical to the TTS auditory exposure function for that hearing group).

    - <u>Impulsive sounds</u>: Based on limited available marine mammal impulsive data, the relationships previously derived in Southall et al. (2007), which relied upon terrestrial mammal growth rates (Henderson and Hamernik 1982; Henderson and Hamernik 1986; Price and Wansack 1989; Levine et al. 1998; Henderson et al. 2008), was used to predict PTS onset:

        - Resulting in an approximate 15 dB difference between TTS and PTS onset thresholds in the $\mathrm{SEL}_{\mathrm{cum}}$ metric.

        - Southall et al. (2007) recommended a 6 dB of TTS/dB of noise growth rate for PK thresholds. This recommendation was based on several factors, including ensuring that the PK acoustic threshold did not unrealistically exceed the cavitation threshold of water. Resulting in an approximate 6 dB difference between TTS and PTS onset thresholds in the PK metric.

III. UPDATING OF ACOUSTIC TECHNICAL GUIDANCE AND THRESHOLDS

Research on the effects of anthropogenic sound on marine mammals has increased dramatically in the last decade and will likely continue to increase in the future. As such, the Technical Guidance will be reviewed periodically and updated as appropriate to reflect the compilation, interpretation, and synthesis of the scientific literature.

NMFS' initial approach for updating current thresholds for protected marine species consisted of providing thresholds for underwater PTS onset for marine mammals via this document. As more data become available, thresholds may be established for additional protected marine species, such as sea turtles and marine fishes. As with this document, public review and outside peer review will be integral to the process.

3.1 PROCEDURE AND TIMELINE FOR UPDATING THE TECHNICAL GUIDANCE

NMFS will continue to monitor and evaluate new data as they become available and periodically convene staff from our various offices, regions, and science centers to update the Technical Guidance as appropriate (anticipating updates to occur on a three to five year cycle). In addition to evaluating new, relevant scientific studies, NMFS will also periodically re-examine basic concepts and definitions (e.g., hearing groups, PTS, TTS, auditory weighting functions), appropriate metrics, temporal and spatial considerations, and other relevant topics. Updates will be posted at Link to Technical Guidance web page.

Since the methodology for deriving composite audiograms and associated marine mammal auditory weighting functions, as well as TTS thresholds is data driven, any new information that becomes available has the potential to cause some amount of change for that specific hearing group but also other hearing groups, if they rely on surrogate data. It may not be feasible to make changes every time a new data point becomes available. Instead, NMFS will periodically examine new data to date and consider the impacts of those studies on the Technical Guidance to determine what revisions/updates may be appropriate. At the same time, there may be special circumstances that merit evaluation of data on a more accelerated timeline (e.g., LF cetacean data that could result in significant changes to the current Technical Guidance).

3.1.1 Consideration for New Scientific Publication

During the Technical Guidance's recent review under EO 13795 (i.e., public comment period; 82 FR 24950; May 31, 2017), several commenters provided information on newly published scientific literature (i.e., 12 publications) for consideration and inclusion in a revised version of the Technical Guidance. NMFS reviewed all literature suggested by commenters. The majority of suggested papers were either already considered within the 2016 Technical Guidance or were not applicable for incorporation (i.e., many newly available marine mammal audiograms were collected via auditory evoked potential (AEP), which cannot be directly incorporated in the current methodology). Of the studies suggested, only the Branstetter et al. 2017 publication, which provides behavioral audiograms for six individual killer whales, was appropriate for consideration within the Technical Guidance. Since the close of the public comment period, a paper providing two new additional behavioral audiograms for harbor porpoise (Kastelein et al. 2017a), a paper examining TTS in harbor porpoise exposed to multiple airgun shots (Kastelein et al. 2017b), and a paper examining TTS in harbor porpoise exposed to mid-frequency sonar playbacks (Kastelein et al. 2017c) were published. These three additional papers are also appropriate for consideration within the Technical Guidance.

The Technical Guidance's methodology (Appendix A) is data driven, meaning every new publication has the potential to result in some change to either the thresholds and/or auditory weighting functions for a single or multiple hearing groups (i.e., those groups whose data are used as surrogates for other hearing groups), and with every change comes a necessary transition period to allow action proponents to adapt to these changes. Thus, there are scientific, as well as practical implications that need consideration before making even a minor a change to the Technical Guidance. One commenter said it best by "The value of a revision of any science-based advice hinges on the balance between the availability of new scientific evidence and the need for a period of stability. The greater the complexity of the advice the greater the need for a long stable period to assimilate that advice before it is updated[35]." The Marine Mammal Commission (MMC) and U.S. Navy offered similar cautions about the practicality of revising the Technical Guidance every time a new study becomes available.

Upon consideration of these most recent studies during our review under EO 13795 and considering recommendations from other Federal agencies and public commenters, NMFS determined it is not practical from an implementation standpoint to add these studies at this time. NMFS will include these studies in the next revision of this document (i.e., Version 3.0) and adhere to our stipulated 3 to 5 year update schedule, where we can evaluate all new relevant publications and make changes in a more predictable manner.

3.1.1.1 Preliminary Analysis of Branstetter et al. 2017, Kastelein et al. 2017a, Kastelein et al. 2017b, and Kastelein et al. 2017c

NMFS conducted a preliminary analysis examining the new data provided in Branstetter et al. 2017, Kastelein et al. 2017a, Kastelein et al. 2017b, and Kastelein et al. 2017c in the context of the Technical Guidance's current MF and HF cetacean composite audiograms (Branstetter et al. 2017; Kastelein et al. 2017a) and HF cetacean TTS/PTS onset thresholds (Kastelein et al. 2017b; Kastelein et al. 2017c).

Branstetter et al. 2017

The Technical Guidance's composite audiogram for MF cetaceans does incorporate behavioral audiograms from two individual killer whales (i.e., Vigga and Yakka from Szymanski et al. 1999). In Figure 3 from the Branstetter et al. 2017 publication, they plot Vigga and Yakka's audiogram data as a comparison to the audiograms obtained to in their study. From this figure and corresponding threshold table (Table 1 in Branstetter et al. 2017), in the killer whale's most sensitive hearing range, the data already included in the Technical Guidance align with Branstetter et al.'s new audiograms, and for most frequencies, Vigga and Yakka have lower thresholds.

Kastelein et al. 2017a

The Technical Guidance's composite audiogram for HF cetaceans does incorporate behavioral audiograms for three harbor porpoises (i.e., PpSH047 and Jerry from Kastelein et al. 2010; ID No. 04 from Kastelein et al. 2015c). In Figure 1 from Kastelein et al. 2017a, they plot their previously published audiograms from these three individuals as a comparison to the two new individual audiograms obtained in this study. Kastelein et al. (2017) concluded from this most recent study "The basic audiograms of the young female and male harbor porpoises in the present study were similar to those of the three previously tested young male harbor porpoises (Fig 1)."

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[35] Link to public comment made on Regulations.gov.

Kastelein et al. 2017b

In this study, a harbor porpoise was exposed to either 10 or 20 consecutive shots from two airings simultaneously. A mean threshold shift of 4.4 dB occurred after exposure to a weighted cumulative level of 140.3 dB. The Technical Guidance's TTS onset threshold (weighted SEL_{cum}) for HF cetaceans and impulsive sources is 140 dB, which is consistent with the results from this most recent study. This paper also concludes, "the initial results indicate that the frequency-weighting function proposed by NOAA (NMFS, 2016) provides a reasonably robust measure of low levels of TTS occurring over a range of spectra of impulsive sound sources."

Kastelein et al. 2017c

This study exposed two harbor porpoises to mid-frequency sonar (3.5 to 4.1 kHz) and reported that to induce a 6 dB threshold shift in harbor porpoises an unweighted cumulative level between 175 and 180 dB would be needed. If these data were weighted using the Technical Guidance's auditory weighting function, the values would be ~157.7 and ~162.7 dB SEL_{cum}[36]. The Technical Guidance's TTS onset threshold (weighted SEL_{cum}) for HF cetaceans and non-impulsive sources is 153 dB, which is consistent with the results from this most recent study (i.e., the thresholds from Kastelein et al. 2017c are likely slightly higher than the Technical Guidance because it was an intermittent source allowing for a greater potential for recovery between pauses of the various signal components).

Preliminary Conclusions

Thus, from this preliminary analysis, NMFS concludes that the Branstetter el. 2017 and Kastelein et al. 2017a audiograms are consistent with data already included in the Technical Guidance for these two species (i.e., the data from these two recent studies align with previous data collected and incorporated within the current version of the Technical Guidance). Additionally, the HF cetacean TTS data presented in Kastelein et al. 2017b and Kastelein et al. 2017c are consistent with the HF cetacean thresholds presented in the Technical Guidance.

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[36] NMFS contacted the authors of this paper to confirm weighted levels.

APPENDIX A: FINNERAN TECHNICAL REPORT

The entire Finneran Technical Report (Finneran 2016), regarding methodology for deriving auditory weighting functions and thresholds for marine mammal species under NMFS' jurisdiction, is included for reference in Appendix A. Its contents have not been modified by NMFS, other than adding "A" before figures and tables to denote Appendix A and be consistent with the other appendices in the Technical Guidance.

Notes:

a. Literature cited in this section are included at the end of this Appendix (i.e., not all references found in this Appendix are included in the Literature Cited for the Technical Guidance). Additionally, terminology, symbols, and abbreviations used in this appendix may not match those used elsewhere in the Technical Guidance.

b. The derivation of the Technical Guidance's thresholds and auditory weighting functions are from two primary sets of data: 1) Audiogram data (used to derive composite audiograms for each hearing group) and 2) TTS onset data (used to derive auditory weighting functions and TTS onset thresholds by hearing group). For each of these two primary data sets, either data points were derived directly from the published study or if data were originally reported in terms of sound pressure level and duration, they converted to sound exposure level via standard relationships.

c. Since the final Finneran Technical Report was received, an additional TTS study became available (Kastelein et al. 2016). Information regarding this study is added as a footnote by NMFS.

d. After the Technical Guidance's finalization, an additional two TTS studies became available (Kastelein et al. 2017b; Kastelein et al. 2017c). In the Kastelein et al. 2017b study, a harbor porpoise was exposed to either 10 or 20 consecutive shots from two airguns simultaneously. Kastelein et al. 2017c exposed two harbor porpoises to mid-frequency sonar (3.5 to 4.1 kHz). The HF cetacean TTS data (i.e., TTS onset levels) presented in these two most recent studies are consistent with the HF cetacean thresholds presented in the Technical Guidance.

e. Additionally, two behavioral audiogram publications became available after the Technical Guidance's finalization in 2016 (Branstetter et al. 2017; Kastelein et al. 2017a). However, upon consideration of these two studies during EO 13795 review of the Technical Guidance, including recommendations from other Federal agencies (e.g. Navy), NMFS determined it is not practical from an implementation standpoint to add these studies at this time (i.e., Version 2.0). NMFS will include these studies in the next revision of this document (i.e., Version 3.0). From this preliminary analysis, NMFS concludes that the Branstetter el. 2017 and Kastelein et al. 2017a audiograms are consistent with data already included in the Technical Guidance for these two species (i.e., the data from these two recent studies align with previous data collected and incorporated within the current version of the Technical Guidance).

TECHNICAL REPORT 3026
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Auditory Weighting Functions and TTS/PTS Exposure Functions for Marine Mammals Exposed to Underwater Noise

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ADMINISTRATIVE INFORMATION

This work described in this report was prepared for Commander, U.S. Fleet Forces Command, Norfolk, VA, by the Marine Mammal Scientific & Vet Support Branch (Code 71510) of the Biosciences Division (Code 71500), Space and Naval Warfare Systems Center Pacific (SSC Pacific), San Diego, CA.

Released under authority of
M. J. Xitco, Head
Biosciences Division

EXECUTIVE SUMMARY

The US Navy’s Tactical Training Theater Assessment and Planning (TAP) Program addresses environmental challenges that affect Navy training ranges and operating areas. As part of the TAP process, acoustic effects analyses are conducted to estimate the potential effects of Navy activities that introduce high-levels of sound or explosive energy into the marine environment. Acoustic effects analyses begin with mathematical modeling to predict the sound transmission patterns from Navy sources. These data are then coupled with marine species distribution and abundance data to determine the sound levels likely to be received by various marine species. Finally, criteria and thresholds are applied to estimate the specific effects that animals exposed to Navy-generated sound may experience.

This document describes the rationale and steps used to define proposed numeric thresholds for predicting auditory effects on marine mammals exposed to active sonars, other (non-impulsive) active acoustic sources, explosives, pile driving, and air guns for Phase 3 of the TAP Program. Since the derivation of TAP Phase 2 acoustic criteria and thresholds, important new data have been obtained related to the effects of noise on marine mammal hearing. Therefore, for Phase 3, new criteria and thresholds for the onset of temporary and permanent hearing loss have been developed, following a consistent approach for all species of interest and utilizing all relevant, available data. The effects of noise frequency on hearing loss are incorporated by using auditory weighting functions to emphasize noise at frequencies where a species is more sensitive to noise and de-emphasize noise at frequencies where susceptibility is low.

Marine mammals were divided into six groups for analysis: low-frequency cetaceans (group LF: mysticetes), mid-frequency cetaceans (group MF: delphinids, beaked whales, sperm whales), high-frequency cetaceans (group HF: porpoises, river dolphins), sirenians (group SI: manatees), phocids in water (group PW: true seals), and otariids and other non-phocid marine carnivores in water (group OW: sea lions, walruses, otters, polar bears).

For each group, a frequency-dependent weighting function and numeric thresholds for the onset of temporary threshold shift (TTS) and permanent threshold shift (PTS) were derived from available data describing hearing abilities of and effects of noise on marine mammals. The resulting weighting function amplitudes are illustrated in Figure AE-1; Table AE-1 summarizes the parameters necessary to calculate the weighting function amplitudes. For Navy Phase 3 analyses, the onset of TTS is defined as a TTS of 6 dB measured approximately 4 min after exposure. PTS is assumed to occur from exposures resulting in 40 dB or more of TTS measured approximately 4 min after exposure. Exposures just sufficient to cause TTS or PTS are denoted as “TTS onset” or “PTS onset” exposures.

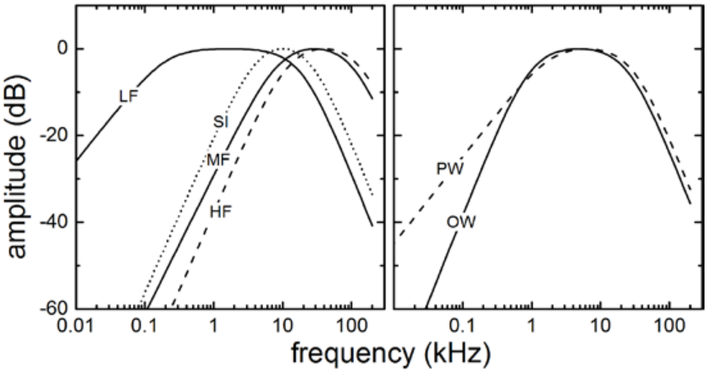

Figure AE-1. **Navy Phase 3 weighting functions for all species groups. Parameters required to generate the functions are provided in Table AE-1.**

Table AE-1. **Summary of weighting function parameters and TTS/PTS thresholds. SEL thresholds are in dB re 1 µPa^{2}s and peak SPL thresholds are in dB re 1 µPa.**

$W(f)=C+10\log_{10}\left\{\frac{(f/f_1)^{2a}}{\left[1+(f/f_1)^2\right]^a\left[1+(f/f_2)^2\right]^b}\right\}$						Non-impulsive		Impulse			
						TTS threshold	PTS threshold	TTS threshold		PTS threshold	
Group	*a*	*b*	*f*$_1$ (kHz)	*f*$_2$ (kHz)	*C* (dB)	SEL (weighted)	SEL (weighted)	SEL (weighted)	peak SPL (unweighted)	SEL (weighted)	peak SPL (unweighted)
LF	1	2	0.20	19	0.13	179	199	168	213	183	219
MF	1.6	2	8.8	110	1.20	178	198	170	224	185	230
HF	1.8	2	12	140	1.36	153	173	140	196	155	202
SI	1.8	2	4.3	25	2.62	186	206	175	220	190	226
OW	2	2	0.94	25	0.64	199	219	188	226	203	232
PW	1	2	1.9	30	0.75	181	201	170	212	185	218

To compare the Phase 3 weighting functions and TTS/PTS thresholds to those used in TAP Phase 2 analyses, both the weighting function shape and the weighted threshold values must be taken into account; the weighted thresholds by themselves only indicate the TTS/PTS threshold at the most susceptible frequency (based on the relevant weighting function). In contrast, the TTS/PTS *exposure functions* incorporate both the shape of the weighting function and the weighted threshold value, they provide the best means of comparing the frequency-dependent TTS/PTS thresholds for Phase 2 and 3. Figures AE-2 and AE-3 compare the TTS/PTS exposure functions for non-impulsive sounds (e.g., sonars) and impulsive sounds (e.g., explosions), respectively, used in TAP Phase 2 and Phase 3.

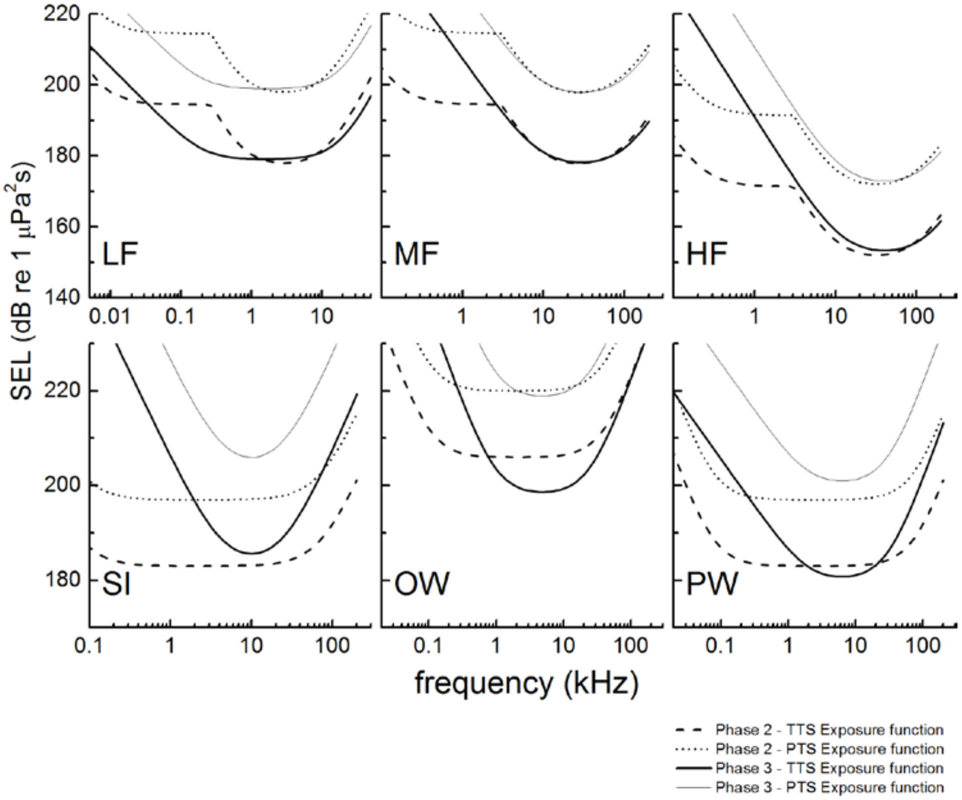

Figure AE-2. **TTS and PTS exposure functions for sonars and other (non-impulsive) active acoustic sources. Heavy solid lines — Navy Phase 3 TTS exposure functions (Table AE-1). Thin solid lines — Navy Phase 3 PTS exposure functions (Table AE-1). Dashed lines — Navy Phase 2 TTS exposure functions. Short dashed lines — Navy Phase 2 PTS exposure functions.**

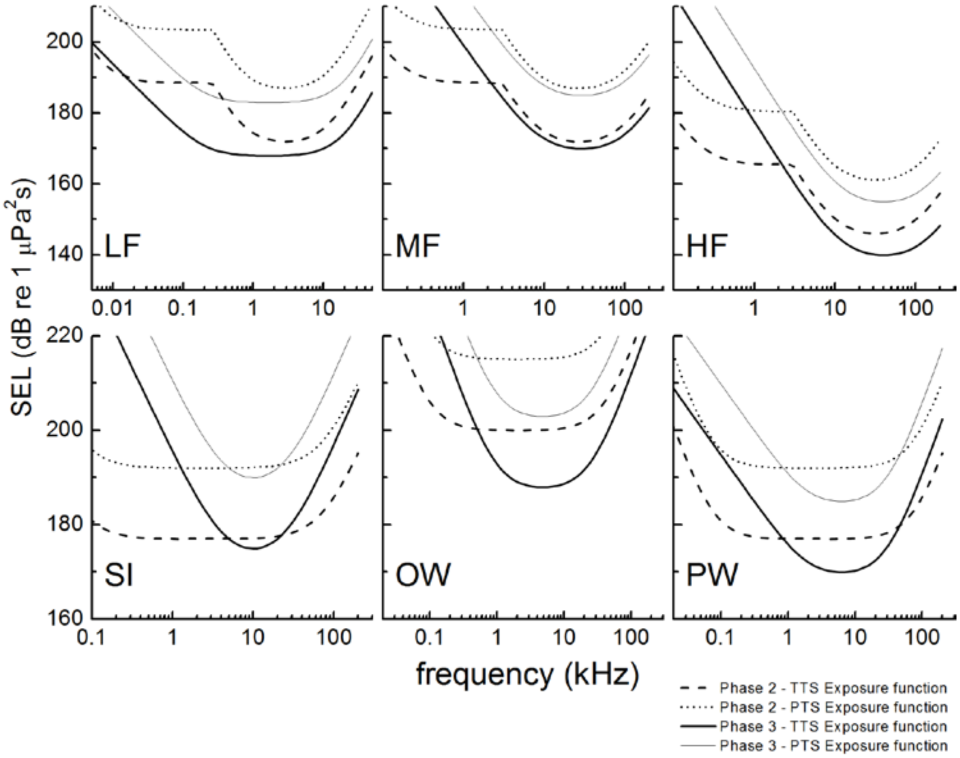

Figure AE-3. **TTS and PTS exposure functions for explosives, impact pile driving, air guns, and other impulsive sources. Heavy solid lines — Navy Phase 3 TTS exposure functions (Table AE-1). Thin solid lines — Navy Phase 3 PTS exposure functions (Table AE-1). Dashed lines — Navy Phase 2 TTS exposure functions. Short dashed lines — Navy Phase 2 PTS exposure functions.**

The most significant differences between the Phase 2 and Phase 3 functions include: (1) Thresholds at low frequencies are generally higher for Phase 3 compared to Phase 2. This is because the Phase 2 weighting functions utilized the “M-weighting” functions at lower frequencies, where no TTS existed at that time. Since derivation of the Phase 2 weighting functions, additional data have been collected to support the use of new functions more similar to human auditory weighting functions. (2) Impulsive TTS/PTS thresholds near the region of best hearing sensitivity are lower for Phase 3 compared to Phase 2.

I. INTRODUCTION

1.1 OVERVIEW

The US Navy's Tactical Training Theater Assessment and Planning (TAP) Program addresses environmental challenges that affect Navy training ranges and operating areas. As part of the TAP process, acoustic effects analyses are conducted to estimate the potential effects of Navy training and testing activities that introduce high-levels of sound or explosive energy into the marine environment. Acoustic effects analyses begin with mathematical modeling to predict the sound transmission patterns from Navy sources. These data are then coupled with marine species distribution and abundance data to determine sound levels likely to be received by various marine species. Finally, criteria and thresholds are applied to estimate the specific effects that animals exposed to Navy-generated sound may experience.

This document describes the rationale and steps used to define proposed numeric thresholds for predicting auditory effects on marine mammals exposed to underwater sound from active sonars, other (non-impulsive) active acoustic sources, explosives, pile driving, and air guns for Phase 3 of the TAP Program. The weighted threshold values and auditory weighting function shapes are summarized in Section 12.

1.2 IMPULSE VS. NON-IMPULSIVE NOISE

When analyzing the auditory effects of noise exposure, it is often helpful to broadly categorize noise as either impulse noise — noise with high peak sound pressure, short duration, fast rise-time, and broad frequency content — or non-impulsive (i.e., steady-state) noise. When considering auditory effects, sonars, other coherent active sources, and vibratory pile driving are considered to be non-impulsive sources, while explosives, impact pile driving, and air guns are treated as impulsive sources. Note that the terms non-impulsive or steady-state do not necessarily imply long duration signals, only that the acoustic signal has sufficient duration to overcome starting transients and reach a steady-state condition. For harmonic signals, sounds with duration greater than approximately 5 to 10 cycles are generally considered to be steady-state.

1.3 NOISE-INDUCED THRESHOLD SHIFTS

Exposure to sound with sufficient duration and sound pressure level (SPL) may result in an elevated hearing threshold (i.e., a loss of hearing sensitivity), called a noise-induced threshold shift (NITS). If the hearing threshold eventually returns to normal, the NITS is called a temporary threshold shift (TTS); otherwise, if thresholds remain elevated after some extended period of time, the remaining NITS is called a permanent threshold shift (PTS). TTS and PTS data have been used to guide the development of safe exposure guidelines for people working in noisy environments. Similarly, TTS and PTS criteria and thresholds form the cornerstone of Navy analyses to predict auditory effects in marine mammals incidentally exposed to intense underwater sound during naval activities.

1.4 AUDITORY WEIGHTING FUNCTIONS

Animals are not equally sensitive to noise at all frequencies. To capture the frequency-dependent nature of the effects of noise, *auditory weighting functions* are used. Auditory weighting functions are mathematical functions used to emphasize frequencies where animals are more susceptible to noise exposure and de-emphasize frequencies where animals are less susceptible. The functions may be thought of as frequency-dependent filters that are applied to a noise exposure before a single, weighted SPL or sound exposure level (SEL) is calculated. The filter shapes are normally “band-pass” in nature; i.e., the function amplitude resembles an inverted “U” when plotted versus frequency. The weighting function amplitude is approximately flat within a limited range of frequencies, called the “pass-band,” and declines at frequencies below and above the pass-band.

Auditory weighting functions for humans were based on *equal loudness contours* — curves that show the combinations of SPL and frequency that result in a sensation of equal loudness in a human listener. Equal loudness contours are in turn created from data collected during loudness comparison tasks. Analogous tasks are difficult to perform with non-verbal animals; as a result, equal loudness contours are available for only a single marine mammal (a dolphin) across a limited range of frequencies (2.5 to 113 kHz) (Finneran and Schlundt, 2011). In lieu of performing loudness comparison tests, reaction times to tones can be measured, under the assumption that reaction time is correlated with subjective loudness (Stebbins, 1966; Pfingst et al., 1975). From the reaction time vs. SPL data, curves of equal response latency can be created and used as proxies for equal loudness contours.

Just as human damage risk criteria use auditory weighting functions to capture the frequency-dependent aspects of noise, US Navy acoustic impact analyses use weighting functions to capture the frequency-dependency of TTS and PTS in marine mammals.

1.5 TAP PHASE 3 WEIGHTING FUNCTIONS AND TTS/PTS THRESHOLDS

Navy weighting functions for TAP Phase 2 (Finneran and Jenkins, 2012) were based on the “M-weighting” curves defined by Southall et al. (2007), with additional high-frequency emphasis for cetaceans based on equal loudness contours for a bottlenose dolphin (Finneran and Schlundt, 2011). Phase 2 TTS/PTS thresholds also relied heavily on the recommendations of Southall et al. (2007), with modifications based on preliminary data for the effects of exposure frequency on dolphin TTS (Finneran, 2010; Finneran and Schlundt, 2010) and limited TTS data for harbor porpoises (Lucke et al., 2009; Kastelein et al., 2011).

Since the derivation of TAP Phase 2 acoustic criteria and thresholds, new data have been obtained regarding marine mammal hearing (e.g., Dow Piniak et al., 2012; Martin et al., 2012; Ghoul and Reichmuth, 2014; Sills et al., 2014; Sills et al., 2015), marine mammal equal latency contours (e.g., Reichmuth, 2013; Wensveen et al., 2014; Mulsow et al., 2015), and the effects of noise on marine mammal hearing (e.g., Kastelein et al., 2012b; Kastelein et al., 2012a; Finneran and Schlundt, 2013; Kastelein et al., 2013a; Kastelein et al., 2013b; Popov et al., 2013; Kastelein et al., 2014b; Kastelein et al., 2014a; Popov et al., 2014; Finneran et al., 2015; Kastelein et al., 2015c; Kastelein et al., 2015b; Popov et al., 2015). As a result, new weighting functions and TTS/PTS thresholds have been developed for Phase 3. The new criteria and thresholds are based on all relevant data and feature a consistent approach for all species of interest.

Marine mammals were divided into six groups for analysis. For each group, a frequency-dependent weighting function and numeric thresholds for the onset of TTS and PTS were derived from available data describing hearing abilities and effects of noise on marine mammals. Measured or predicted auditory threshold data, as well as measured equal latency contours, were used to influence the weighting function shape for each group. For species groups for which TTS data are available, the weighting function parameters were adjusted to provide the best fit to the experimental data. The same methods were then applied to other groups for which TTS data did not exist.

II. WEIGHTING FUNCTIONS AND EXPOSURE FUNCTIONS

The shapes of the Phase 3 auditory weighting functions are based on a generic band-pass filter described by

$$W(f) = C + 10\log_{10}\left\{\frac{(f/f_1)^{2a}}{\left[1+(f/f_1)^2\right]^a\left[1+(f/f_2)^2\right]^b}\right\}, \tag{A1}$$

where $W(f)$ is the weighting function amplitude (in dB) at the frequency f (in kHz). The shape of the filter is defined by the parameters C, f_1, f_2, a, and b (Figs. A1 and A2, left panels):

C *weighting function gain* (dB). The value of C defines the vertical position of the curve. Changing the value of C shifts the function up/down. The value of C is often chosen to set the maximum amplitude of W to 0 dB (i.e., the value of C does not necessarily equal the peak amplitude of the curve).

f_1 *low-frequency cutoff* (kHz). The value of f_1 defines the lower limit of the filter pass-band; i.e., the lower frequency at which the weighting function amplitude begins to decline or “roll-off” from the flat, central portion of the curve. The specific amplitude at f_1 depends on the value of a. Decreasing f_1 will enlarge the pass-band of the function (the flat, central portion of the curve).

f_2 *high-frequency cutoff* (kHz). The value of f_2 defines the upper limit of the filter pass-band; i.e., the upper frequency at which the weighting function amplitude begins to roll-off from the flat, central portion of the curve. The amplitude at f_2 depends on the value of b. Increasing f_2 will enlarge the pass-band of the function.

a *low-frequency exponent* (dimensionless). The value of a defines the rate at which the weighting function amplitude declines with frequency at the lower frequencies. As frequency decreases, the change in weighting function amplitude becomes linear with the logarithm of frequency, with a slope of $20a$ dB/decade. Larger values of a result in lower amplitudes at f_1 and steeper rolloffs at frequencies below f_1.

b *high-frequency exponent* (dimensionless). The value of b defines the rate at which the weighting function amplitude declines with frequency at the upper frequencies. As frequency increases, the change in weighting function amplitude becomes linear with the logarithm of frequency, with a slope of $-20b$ dB/decade. Larger values of b result in lower amplitudes at f_2 and steeper rolloffs at frequencies above f_2.

If $a = 2$ and $b = 2$, Eq. (A1) is equivalent to the functions used to define Navy Phase 2 Type I and EQL weighting functions, M-weighting functions, and the human C-weighting function (American National Standards Institute (ANSI), 2001; Southall et al., 2007; Finneran and Jenkins, 2012). The change from fixed to variable exponents for Phase 3 was done to allow the low- and high-frequency rolloffs to match available experimental data. During implementation, the weighting function defined by Eq. (A1) is used in conjunction with a weighted threshold for TTS or PTS expressed in units of SEL.

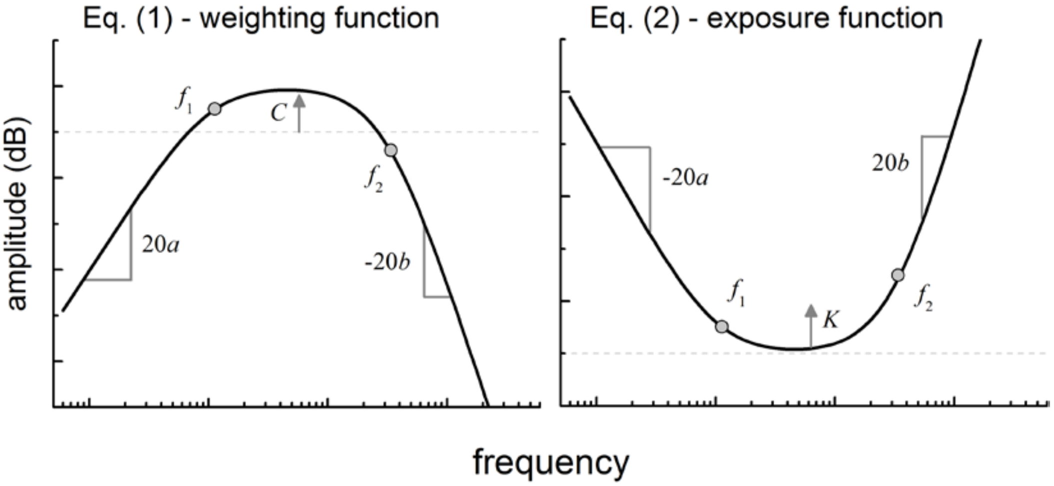

Figure A1. **Examples of (left) weighting function amplitude described by Eq. (A1) and (right) exposure function described by Eq. (A2). The parameters f_1 and f_2 specify the extent of the filter pass-band, while the exponents a and b control the rate of amplitude change below f_1 and above f_2, respectively. As the frequency decreases below f_1 or above f_2, the amplitude approaches linear-log behavior with a slope magnitude of $20a$ or $20b$ dB/decade, respectively. The constants C and K determine the vertical positions of the curves.**

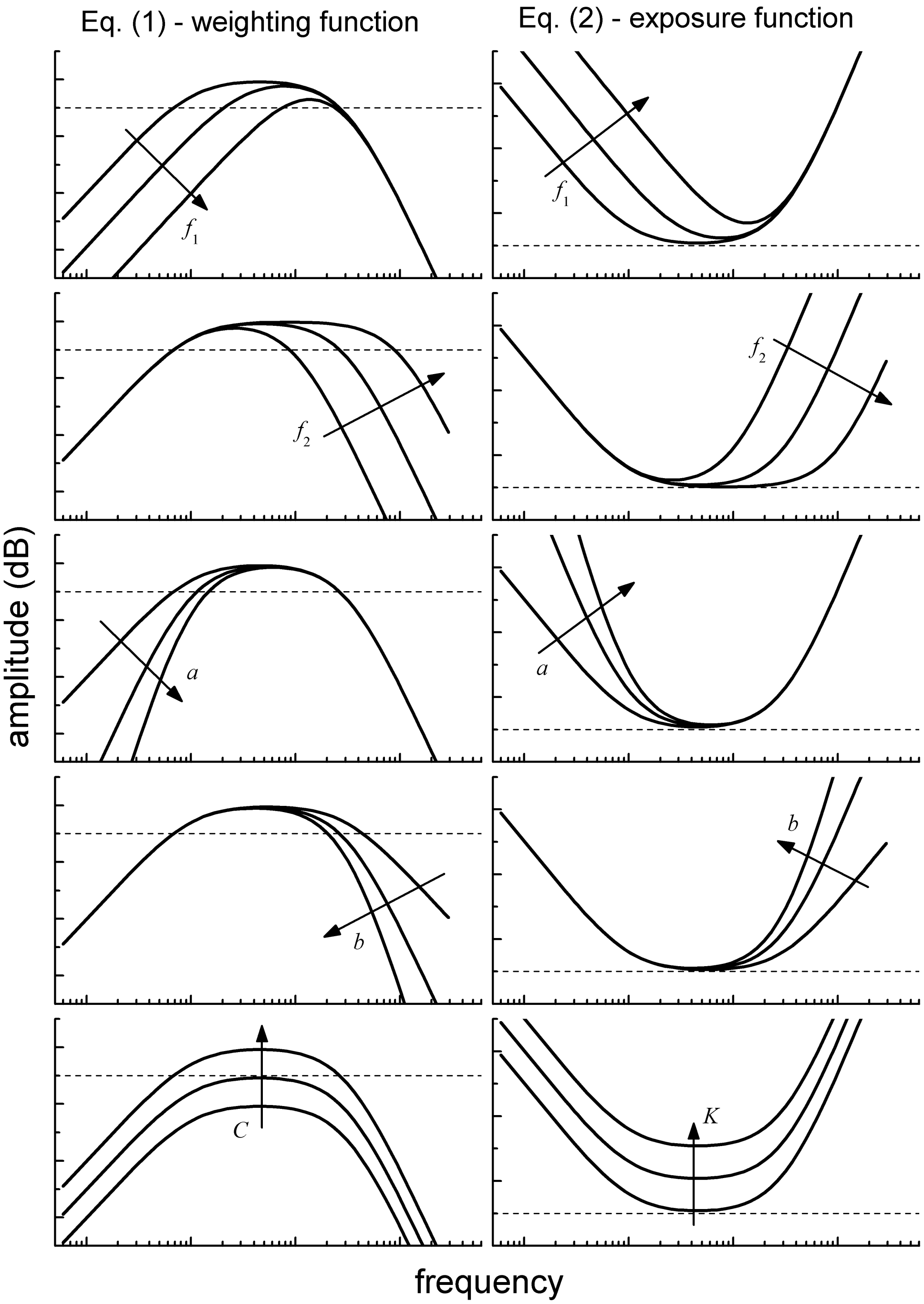

Figure A2. **Influence of parameter values on the resulting shapes of the weighting functions (left) and exposure functions (right). The arrows indicate the direction of change when the designated parameter is increased.**

For developing and visualizing the effects of the various weighting functions, it is helpful to invert Eq. (A1), yielding

$$E(f) = K - 10\log_{10}\left\{\frac{\left(f/f_1\right)^{2a}}{\left[1+\left(f/f_1\right)^2\right]^a\left[1+\left(f/f_2\right)^2\right]^b}\right\}, \tag{A2}$$

where $E(f)$ is the acoustic exposure as a function of frequency f, the parameters f_1, f_2, a, and b are identical to those in Eq. (A1), and K is a constant. The function described by Eq. (A2) has a “U-shape” similar to an audiogram or equal loudness/latency contour (Figs. A1 and A2, right panels). If K is adjusted to set the minimum value of $E(f)$ to match the weighted threshold for the onset of TTS or PTS, Eq. (A2) reveals the manner in which the exposure necessary to cause TTS or PTS varies with frequency. Equation (A2) therefore allows the frequency-weighted threshold values to be directly compared to TTS data. The function defined by Eq. (A2) is referred to as an *exposure function*, since the curve defines the acoustic exposure that equates to TTS or PTS as a function of frequency. To illustrate the relationship between weighting and exposure functions, Fig. A3 shows the Navy Phase 2 weighting function [Eq. (A1), left panel] and TTS exposure function [Eq. (A2), right panel] for mid-frequency cetaceans exposed to sonars.

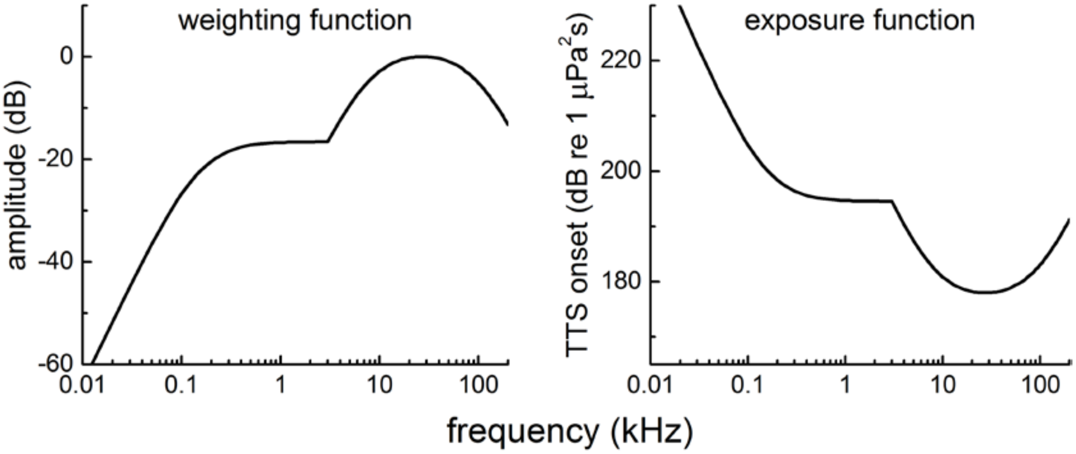

Figure A3. **(left panel) Navy Phase 2 weighting function for the mid-frequency cetacean group. This function was used in conjunction with a weighted TTS threshold of 178 dB re 1 μPa²s. For narrowband signals, the effective, weighted TTS threshold at a particular frequency is calculated by adding the weighting function amplitude at that frequency to the weighted TTS threshold (178 dB re 1 μPa²s). To visualize the frequency-dependent nature of the TTS threshold, the weighting function is inverted and the minimum value set equal to the weighted TTS threshold. This is illustrated in the right panel, which shows the SEL required for TTS onset as a function of frequency. The advantage of this representation is that it may be directly compared to TTS onset data at different exposure frequencies.**

The relationships between Eqs. (A1) and (A2) may be highlighted by defining the function $X(f)$ as

$$X(f) = 10\log_{10}\left\{\frac{(f/f_1)^{2a}}{\left[1+(f/f_1)^2\right]^a\left[1+(f/f_2)^2\right]^b}\right\}. \tag{A3}$$

The peak value of $X(f)$ depends on the specific values of f_1, f_2, a, and b and will not necessarily equal zero. Substituting Eq. (A3) into Eqs. (A1) and (A2) results in

$$W(f) = C + X(f) \tag{A4}$$

and

$$E(f) = K - X(f), \tag{A5}$$

respectively. The maximum of the weighting function and the minimum of the exposure function occur at the same frequency, denoted f_p. The constant C is defined so the weighting function maximum value is 0 dB; i.e., $W(f_p) = 0$, so

$$W(f_p) = 0 = C + X(f_p). \tag{A6}$$

The constant K is defined so that the minimum of the exposure function [i.e., the value of $E(f)$ when $f = f_p$] equals the weighted TTS or PTS threshold, T_{wgt}, so

$$E(f_p) = T_{wgt} = K - X(f_p). \tag{A7}$$

Adding Eqs. (A6) and (A7) results in

$$T_{wgt} = C + K. \tag{A8}$$

The constants C, K, and the weighted threshold are therefore not independent and any one of these parameters can be calculated if the other two are known.

III. METHODOLOGY TO DERIVE FUNCTION PARAMETERS

Weighting and exposure functions are defined by selecting appropriate values for the parameters C, K, f_1, f_2, a, and b in Eqs. (A1) and (A2). Ideally, these parameters would be based on experimental data describing the manner in which the onset of TTS or PTS varied as a function of exposure frequency. In other words, a weighting function for TTS should ideally be based on TTS data obtained using a range of exposure frequencies, species, and individual subjects within each species group. However, at present, there are only limited data for the frequency-dependency of TTS in marine mammals. Therefore, weighting and exposure function derivations relied upon auditory threshold measurements (audiograms), equal latency contours, anatomical data, and TTS data when available.

Although the weighting function shapes are heavily influenced by the shape of the auditory sensitivity curve, the two are not identical. Essentially, the auditory sensitivity curves are adjusted to match the existing TTS data in the frequency region near best sensitivity (step 4 below). This results in "compression" of the auditory sensitivity curve in the region near best sensitivity to allow the weighting function shape to match the TTS data, which show less change with frequency compared to hearing sensitivity curves in the frequency region near best sensitivity.

Weighting and exposure function derivation consisted of the following steps:

1. Marine mammals were divided into six groups based on auditory, ecological, and phylogenetic relationships among species.

2. For each species group, a representative, composite audiogram (a graph of hearing threshold vs. frequency) was estimated.

3. The exponent a was defined using the smaller of the low-frequency slope from the composite audiogram or the low-frequency slope of equal latency contours. The exponent b was set equal to two.

4. The frequencies f_1 and f_2 were defined as the frequencies at which the composite threshold values are ΔT-dB above the lowest threshold value. The value of ΔT was chosen to minimize the mean-squared error between Eq. (2) and the non-impulsive TTS data for the mid- and high-frequency cetacean groups.

5. For species groups for which TTS onset data exist, K was adjusted to minimize the squared error between Eq. (A2) and the steady-state (non-impulsive) TTS onset data. For other species, K was defined to provide the best estimate for TTS onset at a representative frequency. The minimum value of the TTS exposure function (which is not necessarily equal to K) was then defined as the weighted TTS threshold.

6. The constant *C* was defined to set the peak amplitude of the function defined by Eq. (A1) to zero. This is mathematically equivalent to setting C equal to the difference between the weighted threshold and *K* [see Eq. (A8)].

7. The weighted threshold for PTS was derived for each group by adding a constant value (20 dB) to the weighted TTS thresholds. The constant was based on estimates of the difference in exposure levels between TTS onset and PTS onset (i.e., 40 dB of TTS) obtained from the marine mammal TTS growth curves.

8. For the mid- and high-frequency cetaceans, weighted TTS and PTS thresholds for explosives and other impulsive sources were obtained from the available impulse TTS data. For other groups, the weighted SEL thresholds were estimated using the relationship between the steady-state TTS weighted threshold and the impulse TTS weighted threshold for the mid- and high-frequency cetaceans. Peak SPL thresholds were estimated using the relationship between hearing thresholds and the impulse TTS peak SPL thresholds for the mid- and high-frequency cetaceans.

The remainder of this document addresses these steps in detail.

IV. MARINE MAMMAL SPECIES GROUPS

Marine mammals were divided into six groups (Table A1), with the same weighting function and TTS/PTS thresholds used for all species within a group. Species were grouped by considering their known or suspected audible frequency range, auditory sensitivity, ear anatomy, and acoustic ecology (i.e., how they use sound), as has been done previously (e.g., Ketten, 2000; Southall et al., 2007; Finneran and Jenkins, 2012).

4.1 LOW-FREQUENCY (LF) CETACEANS

The LF cetacean group contains all of the mysticetes (baleen whales). Although there have been no direct measurements of hearing sensitivity in any mysticete, an audible frequency range of approximately 10 Hz to 30 kHz has been estimated from observed vocalization frequencies, observed reactions to playback of sounds, and anatomical analyses of the auditory system. A natural division may exist within the mysticetes, with some species (e.g., blue, fin) having better low-frequency sensitivity and others (e.g., humpback, minke) having better sensitivity to higher frequencies; however, at present there is insufficient knowledge to justify separating species into multiple groups. Therefore, a single species group is used for all mysticetes.

4.2 MID-FREQUENCY (MF) CETACEANS

The MF cetacean group contains most delphinid species (e.g., bottlenose dolphin, common dolphin, killer whale, pilot whale), beaked whales, and sperm whales (but not pygmy and dwarf sperm whales of the genus Kogia, which are treated as high-frequency species). Hearing sensitivity has been directly measured for a number of species within this group using psychophysical (behavioral) or auditory evoked potential (AEP) measurements.

4.3 HIGH-FREQUENCY (HF) CETACEANS

The HF cetacean group contains the porpoises, river dolphins, pygmy/dwarf sperm whales, *Cephalorhynchus* species, and some *Lagenorhynchus* species. Hearing sensitivity has been measured for several species within this group using behavioral or AEP measurements. High-frequency cetaceans generally possess a higher upper-frequency limit and better sensitivity at high frequencies compared to the mid-frequency cetacean species.

4.4 SIRENIANS

The sirenian group contains manatees and dugongs. Behavioral and AEP threshold measurements for manatees have revealed lower upper cutoff frequencies and sensitivities compared to the mid-frequency cetaceans.

4.5 PHOCIDS

This group contains all earless seals or “true seals,” including all Arctic and Antarctic ice seals, harbor or common seals, gray seals and inland seals, elephant seals, and monk seals. Underwater hearing thresholds exist for some Northern Hemisphere species in this group.

4.6 OTARIIDS AND OTHER NON-PHOCID MARINE CARNIVORES

This group contains all eared seals (fur seals and sea lions), walruses, sea otters, and polar bears. The division of marine carnivores by placing phocids in one group and all others into a second group was made after considering auditory anatomy and measured audiograms for the various species and noting the similarities between the non-phocid audiograms (Fig. A4). Underwater hearing thresholds exist for some Northern Hemisphere species in this group.

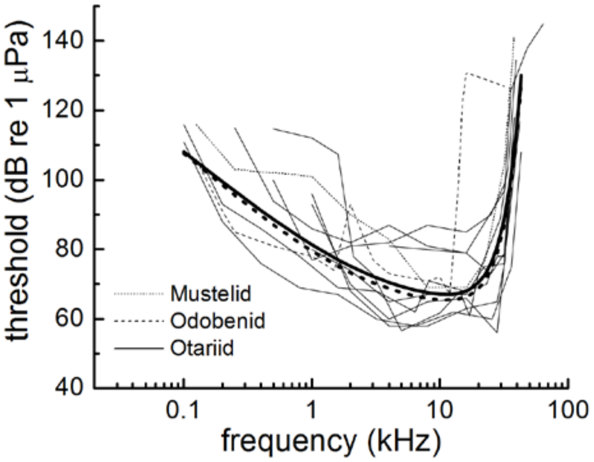

Figure A4. **Comparison of Otariid, Mustelid, and Odobenid psychophysical hearing thresholds measured underwater. The thick, solid line is the composite audiogram based on data for all species. The thick, dashed line is the composite audiogram based on the otariids only.**

Table A1. Species group designations for Navy Phase 3 auditory weighting functions.

Code	Name	Members
LF	Low-frequency cetaceans	Family Balaenidae (right and bowhead whales) Family Balaenopteridae (rorquals) Family Eschrichtiidae (gray whale) Family Neobalaenidae (pygmy right whale)
MF	Mid-frequency cetaceans	Family Ziphiidae (beaked whales) Family Physeteridae (Sperm whale) Family Monodontidae (Irrawaddy dolphin, beluga, narwhal) Subfamily Delphininae (white-beaked/white-sided/ Risso's/bottlenose/spotted/spinner/striped/common dolphins) Subfamily Orcininae (melon-headed whales, false/pygmy killer whale, killer whale, pilot whales) Subfamily Stenoninae (rough-toothed/humpback dolphins) Genus *Lissodelphis* (right whale dolphins) *Lagenorhynchus albirostris* (white-beaked dolphin) *Lagenorhynchus acutus* (Atlantic white-sided dolphin) *Lagenorhynchus obliquidens* (Pacific white-sided dolphin) *Lagenorhynchus obscurus* (dusky dolphin)
HF	High-frequency cetaceans	Family Phocoenidae (porpoises) Family Platanistidae (Indus/Ganges river dolphins) Family Iniidae (Amazon river dolphins) Family Pontoporiidae (Baiji/ La Plata river dolphins) Family Kogiidae (Pygmy/dwarf sperm whales) Genus *Cephalorhynchus* (Commersen's, Chilean, Heaviside's, Hector's dolphins) *Lagenorhynchus australis* (Peale's or black-chinned dolphin) *Lagenorhynchus cruciger* (hourglass dolphin)
SI	Sirenians	Family Trichechidae (manatees) Family Dugongidae (dugongs)
OW	Otariids and other non-phocid marine carnivores (water)	Family Otariidae (eared seals and sea lions) Family Odobenidae (walrus) *Enhydra lutris* (sea otter) *Ursus maritimus* (polar bear)
PW	Phocids (water)	Family Phocidae (true seals)

V. COMPOSITE AUDIOGRAMS

Composite audiograms for each species group were determined by first searching the available literature for threshold data for the species of interest. For each group, all available AEP and psychophysical (behavioral) threshold data were initially examined. To derive the composite audiograms, the following rules were applied:

> 1. For species groups with three or more behavioral audiograms (all groups except LF cetaceans), only behavioral (no AEP) data were used. Mammalian AEP thresholds are typically elevated from behavioral thresholds in a frequency-dependent manner, with increasing discrepancy between AEP and behavioral thresholds at the lower frequencies where there is a loss of phase synchrony in the neurological responses and a concomitant increase in measured AEP thresholds. The frequency-dependent relationship between the AEP and behavioral data is problematic for defining the audiogram slope at low frequencies, since the AEP data will systematically over-estimate thresholds and therefore over-estimate the low-frequency slope of the audiogram. As a result of this rule, behavioral data were used for all marine mammal groups.
>
> For the low-frequency cetaceans, for which no behavioral or AEP threshold data exist, hearing thresholds were estimated by synthesizing information from anatomical measurements, mathematical models of hearing, and animal vocalization frequencies (see Appendix A1).
>
> 2. Data from an individual animal were included only once at a particular frequency. If data from the same individual were available from multiple studies, data at overlapping frequencies were averaged.
>
> 3. Individuals with obvious high-frequency hearing loss for their species or aberrant audiograms (e.g., obvious notches or thresholds known to be elevated for that species due to masking or hearing loss) were excluded.
>
> 4. Linear interpolation was performed within the threshold data for each individual to estimate a threshold value at each unique frequency present in any of the data for that species group. This was necessary to calculate descriptive statistics at each frequency without excluding data from any individual subject.
>
> 5. Composite audiograms were determined using both the original threshold values from each individual (in dB re 1 μPa) and normalized thresholds obtained by subtracting the lowest threshold value for that subject.

Table A2 lists the individual references for the data ultimately used to construct the composite audiograms (for all species groups except the LF cetaceans). From these data, the median (50th percentile) threshold value was calculated at each frequency and fit by the function

$$T(f) = T_0 + A \log_{10}\left(1 + \frac{F_1}{f}\right) + \left(\frac{f}{F_2}\right)^B, \qquad \text{(A9)}$$

where $T(f)$ is the threshold at frequency f, and T_0, F_1, F_2, A, and B are fitting parameters. The median value was used to reduce the influence of outliers. The particular form of Eq. (A9) was chosen to provide linear-log rolloff with variable slope at low frequencies and a steep rise at high frequencies. The form is similar to that used by Popov et al. (2007) to describe dolphin audiograms; the primary difference between the two is the inclusion of two frequency parameters in Eq. (A9), which allows a more shallow slope in the region of best sensitivity. Equation (A9) was fit to the median threshold data using nonlinear regression (National Instruments LabVIEW 2015). The resulting fitting parameters and goodness of fit values (R^2) are provided in Tables 3 and 4 for the original and normalized data, respectively. Equation (A9) was also used to describe the shape of the estimated audiogram for the LF cetaceans, with the parameter values chosen to provide reasonable thresholds based on the limited available data regarding mysticete hearing (see Appendix A1 for details).

Figures A5 and A6 show the original and normalized threshold data, respectively, as well as the composite audiograms based on the fitted curve. The composite audiograms for each species group are compared in Fig. A6. To allow comparison with other audiograms based on the original threshold data, the lowest threshold for the low-frequency cetaceans was estimated to be 54 dB re 1 µPa, based on the median of the thresholds for the other in-water species groups (MF, HF, SI, OW, PW). From the composite audiograms, the frequency of lowest threshold, f_0, and the slope at the lower frequencies, s_0, were calculated (Table A5). For the species with composite audiograms based on experimental data (i.e., all except LF cetaceans), audiogram slopes were calculated across a frequency range of one decade beginning with the lowest frequency present for each group. The low-frequency slope for LF cetaceans was not based on a curve-fit but explicitly defined during audiogram derivation (see Appendix A1).

Table A2. References, species, and individual subjects used to derive the composite audiograms.

Group	Reference	Species	Subjects
MF	(Finneran et al., 2005b)	*Delphinapterus leucas*	Beethoven
	(Szymanski et al., 1999)	*Orcinus orca*	Yaka, Vigga
	(Nachtigall et al., 1995)	*Grampus griseus*	N/a
	(Kastelein et al., 2003)	*Stenella coeruleoalba*	Meyen
	(Lemonds, 1999)	*Tursiops truncatus*	Itsi Bitsy
	(Brill et al., 2001)	*Tursiops truncatus*	CAS
	(Ljungblad et al., 1982)	*Tursiops truncatus*	12-y male
	(Johnson, 1967)	*Tursiops truncatus*	Salty
	(Sauerland and Dehnhardt, 1998)	*Sotalia fluviatilis*	Paco
	(Johnson et al., 1989)	*Delphinapterus leucas*	2-y female
	(White et al., 1978)	*Delphinapterus leucas*	Edwina, Kojak
	(Awbrey et al., 1988)	*Delphinapterus leucas*	Kojak, female, male
	(Thomas et al., 1988)	*Pseudorca crassidens*	I'a nui hahai
	(Finneran et al., 2010b)	*Tursiops truncatus*	TYH
	(Schlundt et al., 2008)	*Tursiops truncatus*	WEN
	(Ridgway et al., 2001)	*Delphinapterus leucas*	MUK, NOC
	(Tremel et al., 1998)	*Lagenorhynchus obliquidens*	female
HF	(Jacobs and Hall, 1972)	*Inia geoffrensis*	male
	(Kastelein et al., 2002a)**	*Phocoena*	PpSH047
	(Kastelein et al., 2010)	*Phocoena*	Jerry
	(Kastelein et al., 2015a)	*Phocoena*	ID No. 04
SI	(Gaspard et al., 2012)	*Trichechus manatus*	Buffet, Hugh
	(Gerstein et al., 1999)	*Trichechus manatus*	Stormy, Dundee
OW	(Moore and Schusterman, 1987)	*Callorhinus ursinus*	Lori, Tobe
	(Babushina et al., 1991)	*Callorhinus ursinus*	N/a
	(Kastelein et al., 2002b)	*Odobenus rosmarus*	Igor
	(Mulsow et al., 2012)	*Zalophus californianus*	JFN
	(Reichmuth and Southall, 2012)	*Zalophus californianus*	Rio, Sam
	(Reichmuth et al., 2013)	*Zalophus californianus*	Ronan
	(Kastelein et al., 2005)	*Eumetopias jubatus*	EjZH021, EjZH022
	(Ghoul and Reichmuth, 2014)	*Enhydra lutris nereis*	Charlie
PW	(Kastak and Schusterman, 1999)	*Mirounga angustirostris*	Burnyce
	(Terhune, 1988)	*Phoca vitulina*	N/a
	(Reichmuth et al., 2013)	*Phoca vitulina*	Sprouts
	(Kastelein et al., 2009)	*Phoca vitulina*	01, 02
	(Sills et al., 2014)	*Phoca largha*	Amak, Tunu
	(Sills et al., 2015)	*Pusa hispida*	Nayak

** Corrected thresholds from Kastelein et al. (2010) were used.

Table A3. **Composite audiogram parameters values for use in Eq. (A9). For all groups except LF cetaceans, values represent the best-fit parameters from fitting Eq. (A9) to experimental threshold data. For the low-frequency cetaceans, parameter values for Eq. (A9) were estimated as described in Appendix A1.**

Group	T_0 (dB)	F_1 (kHz)	F_2 (kHz)	A	B	R^2
LF	53.19	0.412	9.4	20	3.2	–
MF	46.2	25.9	47.8	35.5	3.56	0.977
HF	46.4	7.57	126	42.3	17.1	0.968
SI	-40.4	3990	3.8	37.3	1.7	0.982
OW	63.1	3.06	11.8	30.1	3.23	0.939
PW	43.7	10.2	3.97	20.1	1.41	0.907

Table A4. **Normalized composite audiogram parameters values for use in Eq. (A9). For all groups except LF cetaceans, values represent the best-fit parameters after fitting Eq. (A9) to normalized threshold data. For the low-frequency cetaceans, parameter values for Eq. (A9) were estimated as described in Appendix A1.**

Group	T_0 (dB)	F_1 (kHz)	F_2 (kHz)	A	B	R^2
LF	-0.81	0.412	9.4	20	3.2	–
MF	3.61	12.7	64.4	31.8	4.5	0.960
HF	2.48	9.68	126	40.1	17	0.969
SI	-109	5590	2.62	38.1	1.53	0.963
OW	2.36	0.366	12.8	73.5	3.4	0.958
PW	-39.6	368	2.21	20.5	1.23	0.907

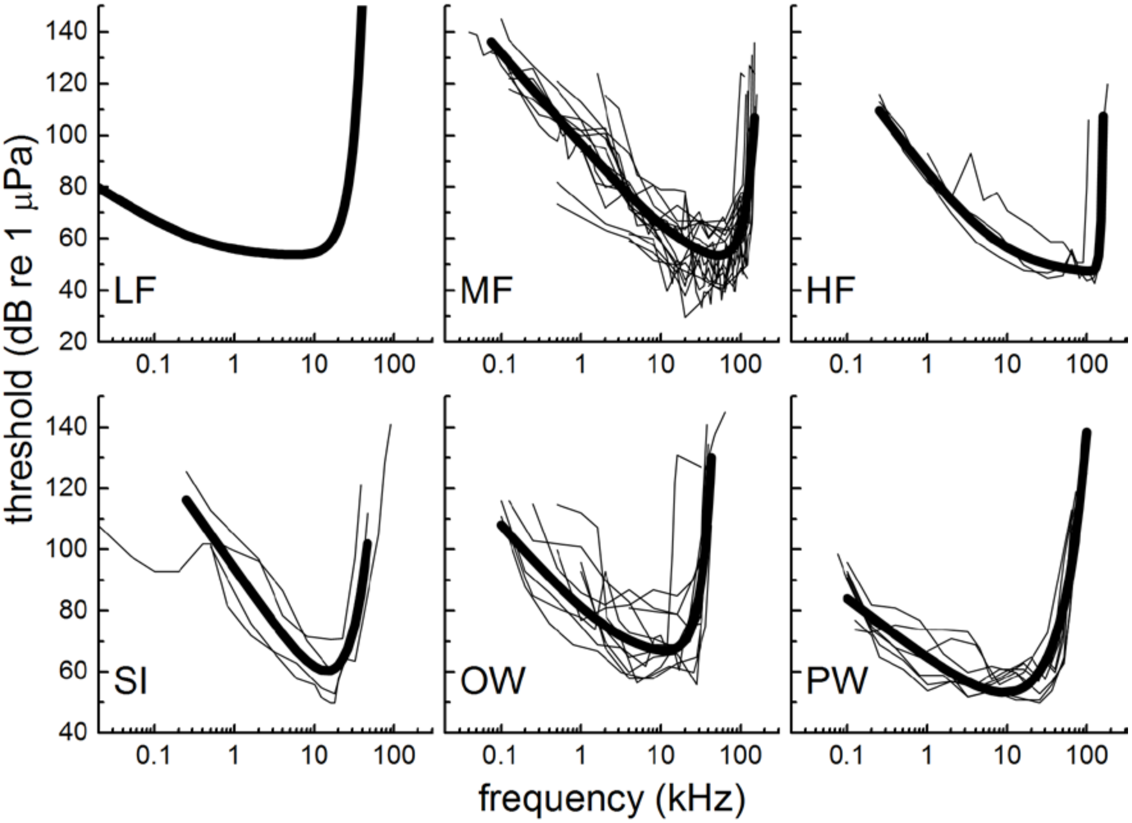

Figure A5. Thresholds and composite audiograms for the six species groups. Thin lines represent the threshold data from individual animals. Thick lines represent either the predicted threshold curve (LF cetaceans) or the best fit of Eq. (A9) to experimental data (all other groups). Derivation of the LF cetacean curve is described in Appendix A1. The minimum threshold for the LF cetaceans was estimated to be 54 dB re 1 µPa, based on the median of the lowest thresholds for the other groups.

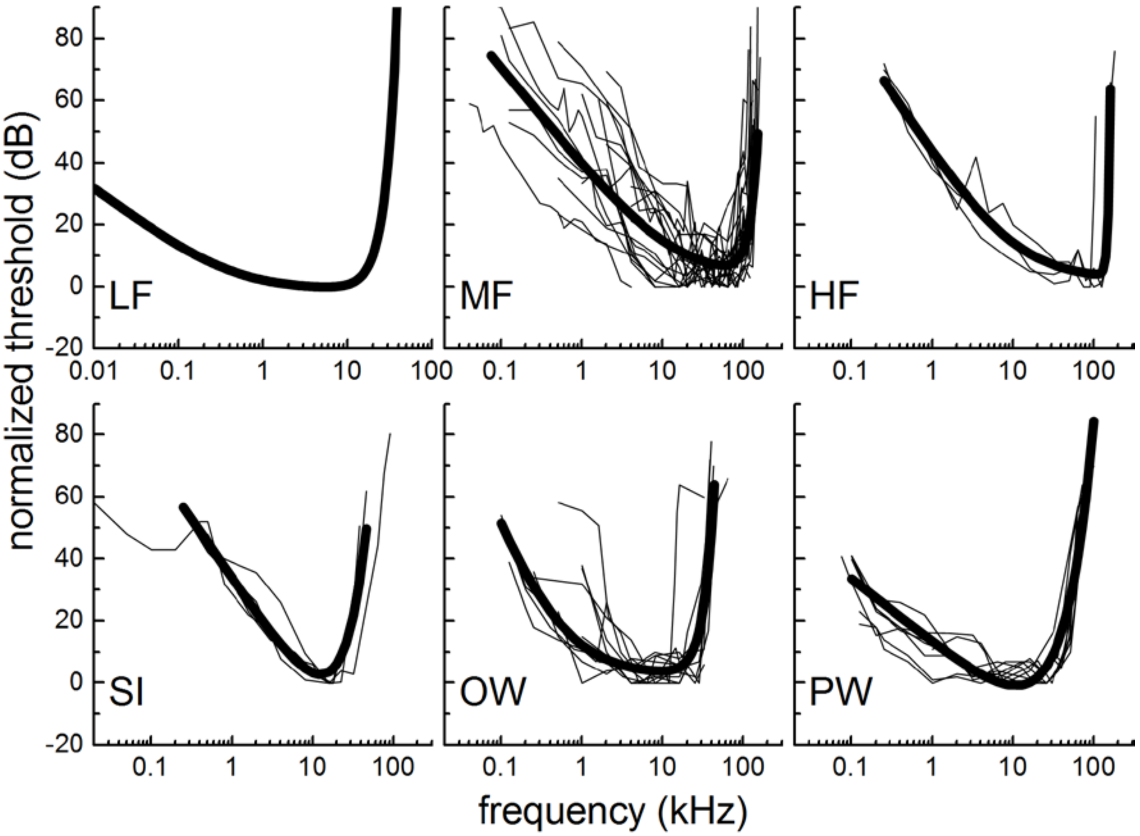

Figure A6. **Normalized thresholds and composite audiograms for the six species groups. Thin lines represent the threshold data from individual animals. Thick lines represent either the predicted threshold curve (LF cetaceans) or the best fit of Eq. (A9) to experimental data (all other groups). Thresholds were normalized by subtracting the lowest value for each individual data set (i.e., within-subject). Composite audiograms were then derived from the individually normalized thresholds (i.e., the composite audiograms were not normalized and may have a minimum value ≠ 0). Derivation of the LF cetacean curve is described in Appendix A1.**

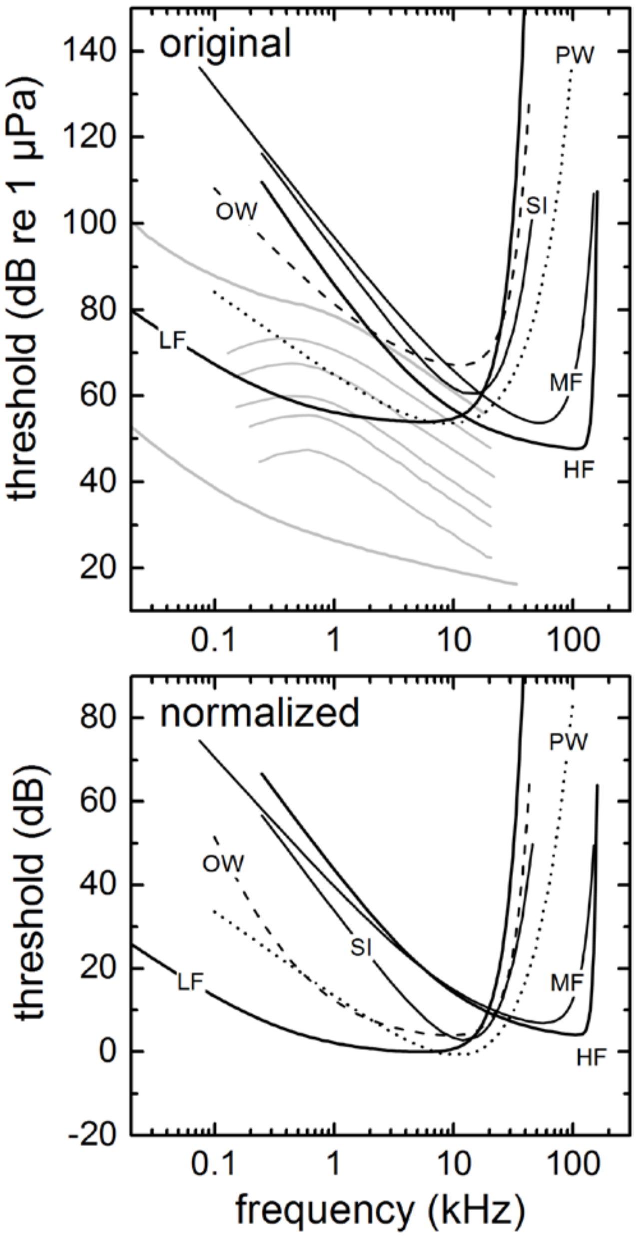

Figure A7. Composite audiograms for the various species groups, derived with the original data (upper) and normalized data (lower). The gray lines in the upper left panel represent ambient noise spectral density levels (referenced to the left ordinate, in dB re 1 µPa^2/Hz) corresponding to the limits of prevailing noise and various sea-state conditions, from 0.5 to 6 (National Research Council (NRC), 2003).

Table A5. **Frequency of best hearing (f_0) and the magnitude of the low-frequency slope (s_0) derived from composite audiograms and equal latency contours. For the species with composite audiograms based on experimental data (i.e., all except LF cetaceans), audiogram slopes were calculated across a frequency range of one decade beginning with the lowest frequency present for each group. The low-frequency slope for LF cetaceans was not based on a curve-fit but explicitly defined during audiogram derivation (see Appendix A1). Equal latency slopes were calculated from the available equal latency contours (Fig. A8).**

Group	Original data composite audiogram		Normalized data composite audiogram		Equal latency curves
	f_0 (kHz)	s_0 (dB/decade)	f_0 (kHz)	s_0 (dB/decade)	s_0 (dB/decade)
LF	5.6	20	5.6	20	—
MF	55	35	58	31	31
HF	105	37	105	36	50
SI	16	36	12	37	—
OW	12	27	10	39	—
PW	8.6	19	13	20	—

VI. EQUAL LOUDNESS DATA

Finneran and Schlundt (2011) conducted a subjective loudness comparison task with a bottlenose dolphin and used the resulting data to derive equal loudness contours and auditory weighting functions. The weighting functions agreed closely with dolphin TTS data over the frequency range 3 to 56 kHz (Finneran and Schlundt, 2013); however, the loudness data only exist for frequencies between 2.5 kHz and 113 kHz and cannot be used to estimate the shapes of loudness contours and weighting functions at lower frequencies.

VII. EQUAL LATENCY DATA

Reaction times to acoustic tones have been measured in several marine mammal species and used to derive equal latency contours and weighting functions (Fig. A8, Wensveen et al., 2014; Mulsow et al., 2015). Unlike the dolphin equal loudness data, the latency data extend to frequencies below 1 kHz and may be used to estimate the slopes of auditory weighting functions at lower frequencies.

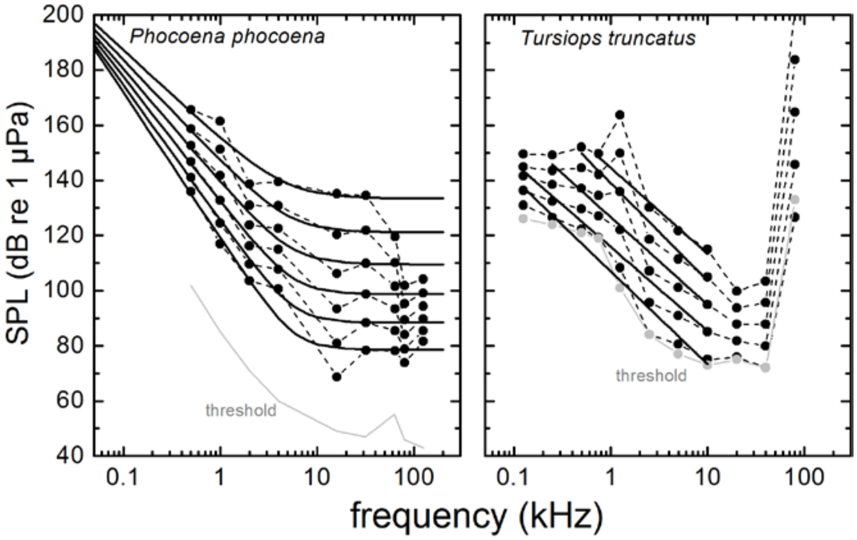

Figure A8. Underwater marine mammal equal latency contours are available for *Phocoena phocoena* (Wensveen et al., 2014) and *Tursiops truncatus* (Mulsow et al., 2015). The slopes for the contours at low frequencies were obtained from the literature (*Phocoena phocoena*) or calculated from the best linear-log fits to the lower frequency data. The slope of the contour passing through an SPL approximately 40 dB above the threshold at f_0 was selected as the most appropriate based on: (1) human A-weighting, (2) observations that the relationship between equal latency and loudness can break down at higher sensation levels, and (3) for many data sets the slopes increase at higher SPLs rather than decrease as expected. The resulting slopes are listed in Table A5.

VIII. TTS DATA

8.1 NON-IMPULSIVE (STEADY-STATE) EXPOSURES – TTS

For weighting function derivation, the most critical data required are TTS onset exposure levels as a function of exposure frequency. These values can be estimated from published literature by examining TTS as a function of SEL for various frequencies.

To estimate TTS onset values, only TTS data from psychophysical (behavioral) hearing tests were used. Studies have shown differences between the amount of TTS from behavioral threshold measurements and that determined using AEP thresholds (Fig. A9). TTS determined from AEP thresholds is typically larger than that determined behaviorally, and AEP-measured TTS of up to ~ 10 dB has been observed with no corresponding change in behavioral thresholds (e.g., Finneran et al., 2007). Although these data suggest that AEP amplitudes and thresholds provide more sensitive indicators (than behavioral thresholds) of the auditory effects of noise, Navy acoustic impact analyses use TTS both as an indicator of the disruption of behavioral patterns that are mediated by the sense of hearing and to predict when the onset of PTS is likely to occur. Navy analyses assume that exposures resulting in a NITS > 40 dB measured a few minutes after exposure will result in some amount of residual PTS. This is based on relationships observed in early human TTS studies utilizing psychophysical threshold measurements. To date, there have been no reports of PTS in a marine mammal whose initial behavioral threshold shift was 40 dB or less; however, behavioral shifts of 35 to 40 dB have required multiple days to recover, suggesting that these exposures are near those capable of resulting in PTS. In contrast, studies utilizing AEP measurements in marine mammals have reported TTSs of 45 dB that recovered in 40 min and 60 dB that recovered in < 24 h, suggesting that these exposures were not near those capable of resulting in PTS (Popov et al., 2013).

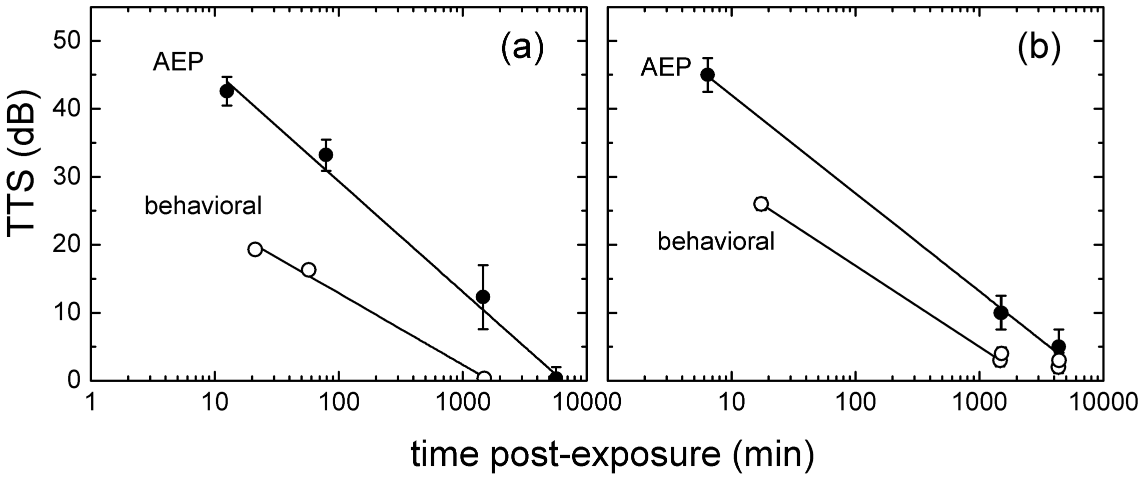

Figure A9. TTS measured using behavioral and AEP methods do not necessarily agree, with marine mammal studies reporting larger TTS obtained using AEP methods. For the data above, thresholds were determined using both techniques before and after the same noise exposure. Hearing thresholds were measured at 30 kHz. Behavioral thresholds utilized FM tones with 10% bandwidth. AEP thresholds were based on AM tones with a modulation frequency of 1.05 kHz. Noise exposures consisted of (a) a single, 20-kHz tone with duration of 64 s and SPL of 185 dB re 1 µPa (SEL = 203 dB re 1 µPa^{2}s) and (b) three 16-s tones at 20 kHz, with mean SPL = 193 dB re 1 µPa (cumulative SEL = 210 dB re 1 µPa^{2}s). Data from Finneran et al. (2007).

To determine TTS onset for each subject, the amount of TTS observed after exposures with different SPLs and durations were combined to create a single TTS growth curve as a function of SEL. The use of (cumulative) SEL is a simplifying assumption to accommodate sounds of various SPLs, durations, and duty cycles. This is referred to as an "equal energy" approach, since SEL is related to the energy of the sound and this approach assumes exposures with equal SEL result in equal effects, regardless of the duration or duty cycle of the sound. It is well-known that the equal energy rule will over-estimate the effects of intermittent noise, since the quiet periods between noise exposures will allow some recovery of hearing compared to noise that is continuously present with the same total SEL (Ward, 1997). For continuous exposures with the same SEL but different durations, the exposure with the longer duration will also tend to produce more TTS (e.g., Kastak et al., 2007; Mooney et al., 2009; Finneran et al., 2010b). Despite these limitations, however, the equal energy rule is still a useful concept, since it includes the effects of both noise amplitude and duration when predicting auditory effects. SEL is a simple metric, allows the effects of multiple noise sources to be combined in a meaningful way, has physical significance, and is correlated with most TTS growth data reasonably well — in some cases even across relatively large ranges of exposure duration (see Finneran, 2015). The use of cumulative SEL for Navy sources will always over-estimate the effects of intermittent or interrupted sources, and the majority of Navy sources feature durations shorter than the exposure durations typically utilized in marine mammal TTS studies, therefore the use of (cumulative) SEL will tend to over-estimate the effects of many Navy sound sources.

Marine mammal studies have shown that the amount of TTS increases with SEL in an accelerating fashion: At low exposure SELs, the amount of TTS is small and the growth curves have shallow slopes. At higher SELs, the growth curves become steeper and approach linear relationships with the noise SEL. Accordingly, TTS growth data were fit with the function

$$t(L) = m_1 \log_{10}\left[1 + 10^{(L-m_2)/10}\right], \tag{A10}$$

where t is the amount of TTS, L is the SEL, and m_1 and m_2 are fitting parameters. This particular function has an increasing slope when $L < m_2$ and approaches a linear relationship for $L > m_2$ (Maslen, 1981). The linear portion of the curve has a slope of $m_1/10$ and an x-intercept of m_2. After fitting Eq. (10) to the TTS growth data, interpolation was used to estimate the SEL necessary to induce 6 dB of TTS — defined as the "onset of TTS" for Navy acoustic impact analyses. The value of 6 dB has been historically used to distinguish non-trivial amounts of TTS from fluctuations in threshold measurements that typically occur across test sessions. Extrapolation was not performed when estimating TTS onset; this means only data sets with exposures producing TTS both above and below 6 dB were used.

Figures A10 to A13 show all behavioral and AEP TTS data to which growth curves defined by Eq. (A10) could be fit. The TTS onset exposure values, growth rates, and references to these data are provided in Table A6.

8.2 NON-IMPULSIVE (STEADY-STATE) EXPOSURES – PTS

Since no studies have been designed to intentionally induce PTS in marine mammals (but see Kastak et al., 2008), onset-PTS levels for marine mammals must be estimated. Differences in auditory structures and sound propagation and interaction with tissues prevent direct application of numerical thresholds for PTS in terrestrial mammals to marine mammals; however, the inner ears of marine and terrestrial mammals are analogous and certain relationships are expected to hold for both groups. Experiments with marine mammals have revealed similarities between marine and terrestrial mammals with respect to features such as TTS, age-related hearing loss, ototoxic drug-induced hearing loss, masking, and frequency selectivity (e.g., Nachtigall et al., 2000; Finneran et al., 2005b). For this reason, relationships between TTS and PTS from marine and terrestrial mammals can be used, along with TTS onset values for marine mammals, to estimate exposures likely to produce PTS in marine mammals (Southall et al., 2007).

A variety of terrestrial and marine mammal data sources (e.g., Ward et al., 1958; Ward et al., 1959; Ward, 1960; Miller et al., 1963; Kryter et al., 1966) indicate that threshold shifts up to 40 to 50 dB may be induced without PTS, and that 40 dB is a conservative upper limit for threshold shift to prevent PTS; i.e., for impact analysis, 40 dB of NITS is an upper limit for reversibility and that any additional exposure will result in some PTS. This means that 40 dB of TTS, measured a few minutes after exposure, can be used as a conservative estimate for the onset of PTS. An exposure causing 40 dB of TTS is therefore considered equivalent to PTS onset.

To estimate PTS onset, TTS growth curves based on more than 20 dB of measured TTS were extrapolated to determine the SEL required for a TTS of 40 dB. The SEL difference between TTS onset and PTS onset was then calculated. The requirement that the maximum amount of TTS must be at least 20 dB was made to avoid over-estimating PTS onset by using growth curves based on small amounts of TTS, where the growth rates are shallower than at higher amounts of TTS.

8.3 IMPULSIVE EXPOSURES

Marine mammal TTS data from impulsive sources are limited to two studies with measured TTS of 6 dB or more: Finneran et al. (2002) reported behaviorally-measured TTSs of 6 and 7 dB in a beluga exposed to single impulses from a seismic water gun (unweighted SEL = 186 dB re 1 μPa^{2}s, peak SPL = 224 dB re 1 μPa) and Lucke et al. (2009) reported AEP-measured TTS of 7 to 20 dB in a harbor porpoise exposed to single impulses from a seismic air gun [Fig. A12(f), TTS onset = unweighted SEL of 162 dB re 1 μPa^{2}s or peak SPL of 195 dB re 1 μPa]. The small reported amounts of TTS and/or the limited distribution of exposures prevent these data from being used to estimate PTS onset.

In addition to these data, Kastelein et al. (2015c)[37] reported behaviorally-measured mean TTS of 4 dB at 8 kHz and 2 dB at 4 kHz after a harbor porpoise was exposed to a series of impulsive sounds produced by broadcasting underwater recordings of impact pile driving strikes through underwater sound projectors. The exposure contained 2760 individual impulses presented at an interval of 1.3 s (total exposure time was 1 h). The average single-strike, unweighted SEL was approximately 146 dB re 1 μPa^{2}s and the cumulative (unweighted) SEL was approximately 180 dB re 1 μPa^{2}s. The pressure waveforms for the simulated pile strikes exhibited significant “ringing” not present in the original recordings and most of the energy in the broadcasts was between 500 and 800 Hz, near the resonance of the underwater sound projector used to broadcast the signal. As a result, some questions exist regarding whether the fatiguing signals were representative of underwater pressure signatures from impact pile driving.

Several impulsive noise exposure studies have also been conducted without measurable (behavioral) TTS. Finneran et al. (2000) exposed dolphins and belugas to single impulses from an “explosion simulator” (maximum unweighted SEL = 179 dB re 1 μPa^{2}s, peak SPL = 217 dB re 1 μPa) and Finneran et al. (2015) exposed three dolphins to sequences of 10 impulses from a seismic air gun (maximum unweighted cumulative SEL = 193 to 195 dB re 1 μPa^{2}s, peak SPL =196 to 210 dB re 1 μPa) without measurable TTS. Finneran et al. (2003) exposed two sea lions to single impulses from an arc-gap

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[37] Footnote added by NMFS: Since the NMFS received this version of the Finneran Technical Report, another TTS study became available (Kastelein et al. 2016). In this study, two harbor porpoises were exposed to playbacks of impact pile driving strikes. Neither individual had a TTS of 6 dB after exposure. Kastelein et al. 2016 estimated TTS onset to occur at SEL_{cum} 175 dB (unweighted).

transducer with no measurable TTS (maximum unweighted SEL = 163 dB re 1 μPa^2s, peak SPL = 203 dB re 1 μPa). Reichmuth et al. (2016) exposed two spotted seals (*Phoca largha*) and two ringed seals (*Pusa hispida*) to single impulses from a 10 in^3 sleeve air gun with no measurable TTS (maximum unweighted SEL = 181 dB re 1 μPa^2s, peak SPL ~ 203 dB re 1 μPa).

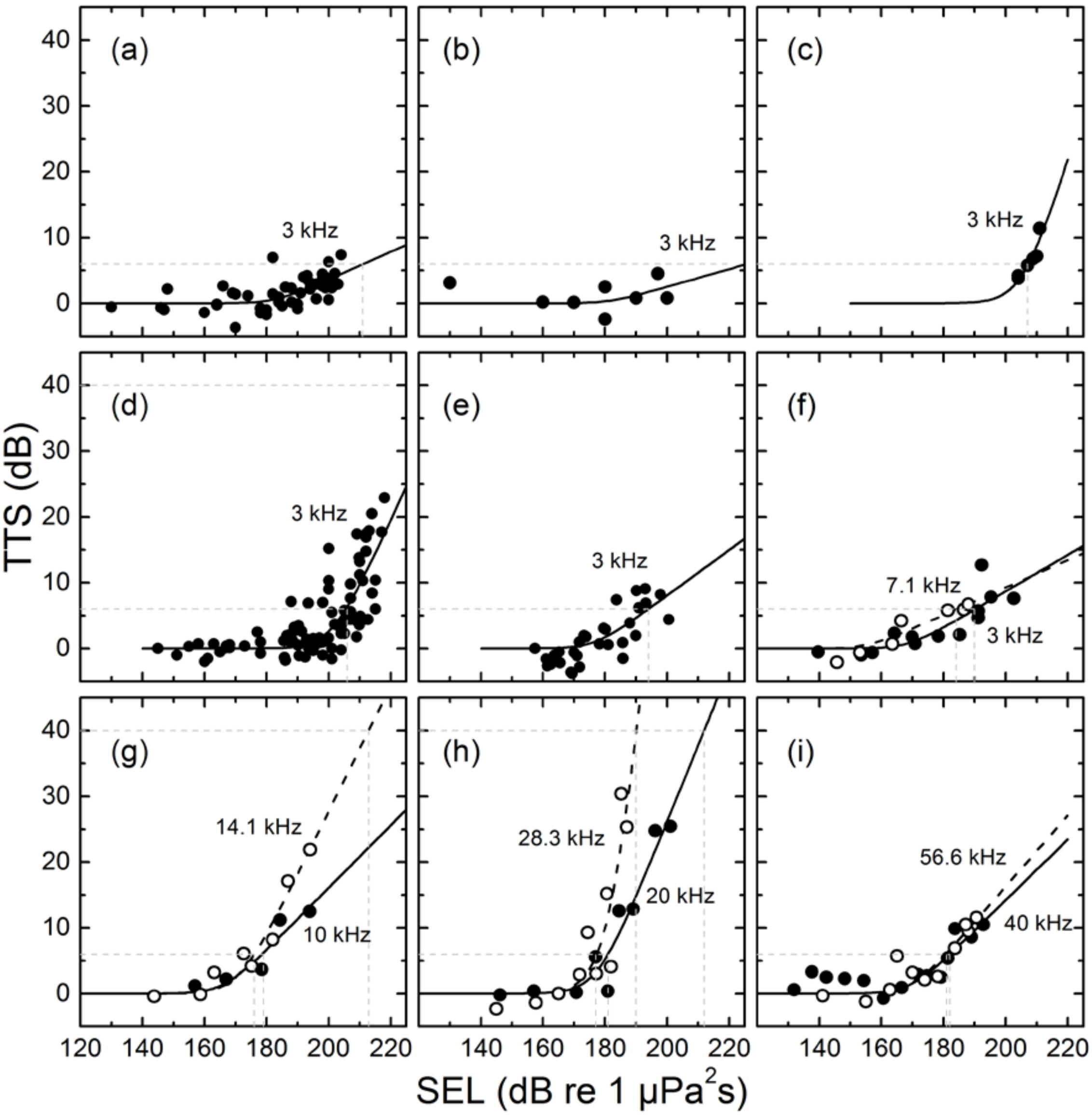

Figure A10. **TTS growth data for mid-frequency cetaceans obtained using behavioral methods. Growth curves were obtained by fitting Eq. (A10) to the TTS data as a function of SEL. Onset TTS was defined as the SEL value from the fitted curve at a TTS = 6 dB, for only those datasets that bracketed 6 dB of TTS. Onset PTS was defined as the SEL value from the fitted curve at a TTS = 40 dB, for only those datasets with maximum TTS > 20 dB. Frequency values within the panels indicate the exposure frequencies. Solid lines are fit to the filled symbols; dashed lines are fit to the open symbols. See Table A6 for explanation of the datasets in each panel. Frequencies listed in each panel denote the exposure frequency.**

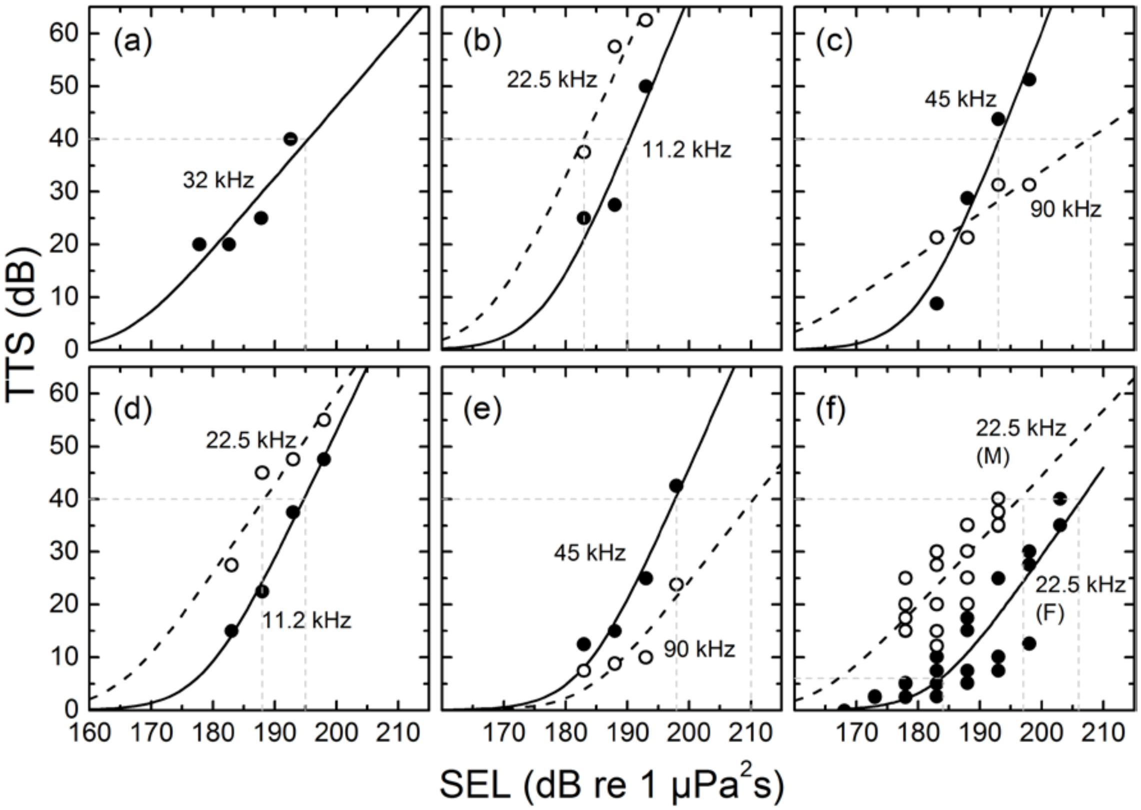

Figure A11. TTS growth data for mid-frequency cetaceans obtained using AEP methods. Growth curves were obtained by fitting Eq. (A10) to the TTS data as a function of SEL. Onset TTS was defined as the SEL value from the fitted curve at a TTS = 6 dB, for only those datasets that bracketed 6 dB of TTS. Onset PTS was defined as the SEL value from the fitted curve at a TTS = 40 dB, for only those datasets with maximum TTS > 20 dB. Frequency values within the panels indicate the exposure frequencies. Solid lines are fit to the filled symbols; dashed lines are fit to the open symbols. See Table A6 for explanation of the datasets in each panel.

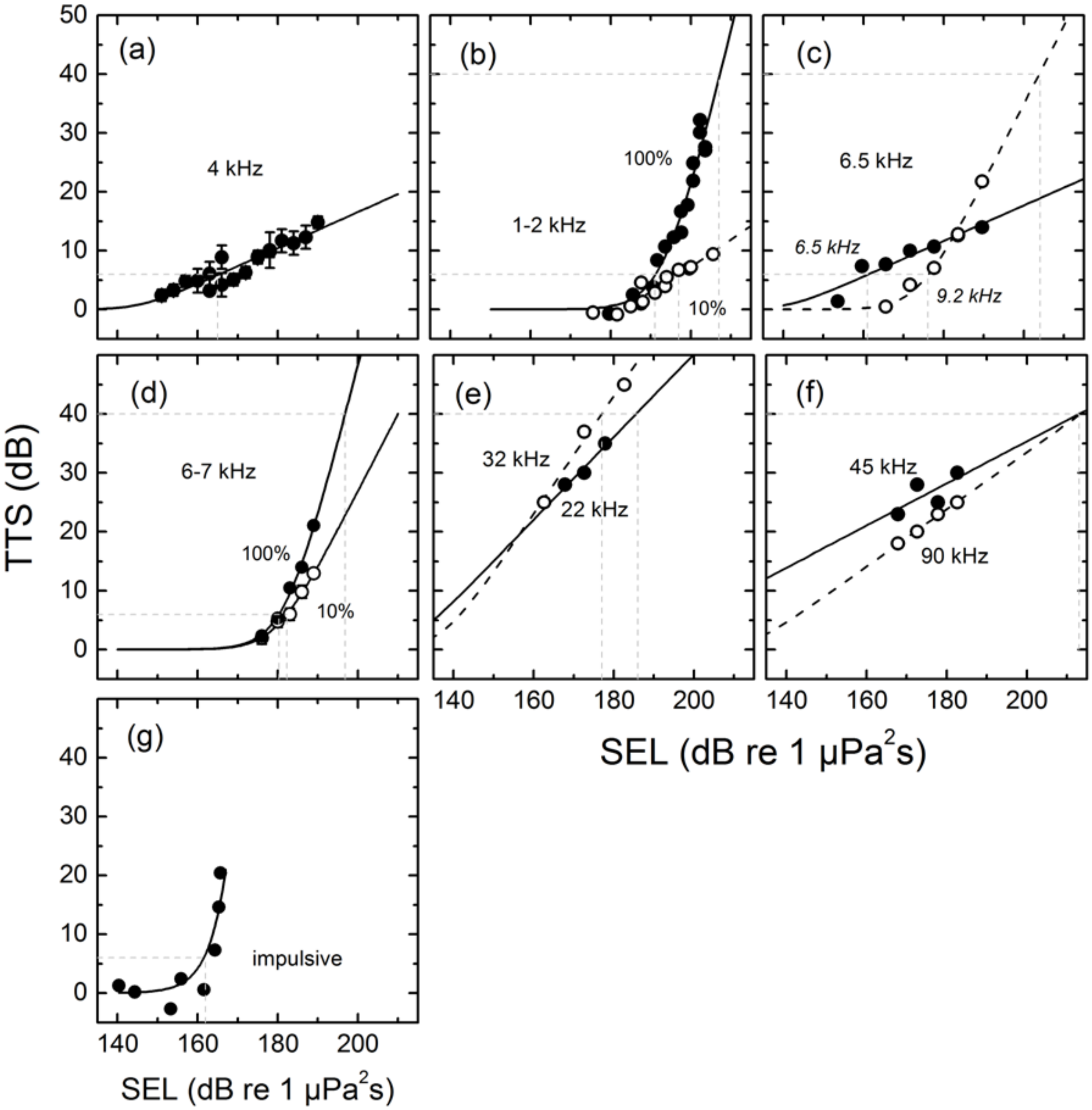

Figure A12. **TTS growth data for high-frequency cetaceans obtained using behavioral and AEP methods. Growth curves were obtained by fitting Eq. (A10) to the TTS data as a function of SEL. Onset TTS was defined as the SEL value from the fitted curve at a TTS = 6 dB, for only those datasets that bracketed 6 dB of TTS. Onset PTS was defined as the SEL value from the fitted curve at a TTS = 40 dB, for only those datasets with maximum TTS > 20 dB. The exposure frequency is specified in normal font; italics indicate the hearing test frequency. Percentages in panels (b), (d) indicate exposure duty cycle (duty cycle was 100% for all others). Solid lines are fit to the filled symbols; dashed lines are fit to the open symbols. See Table A6 for explanation of the datasets in each panel.**

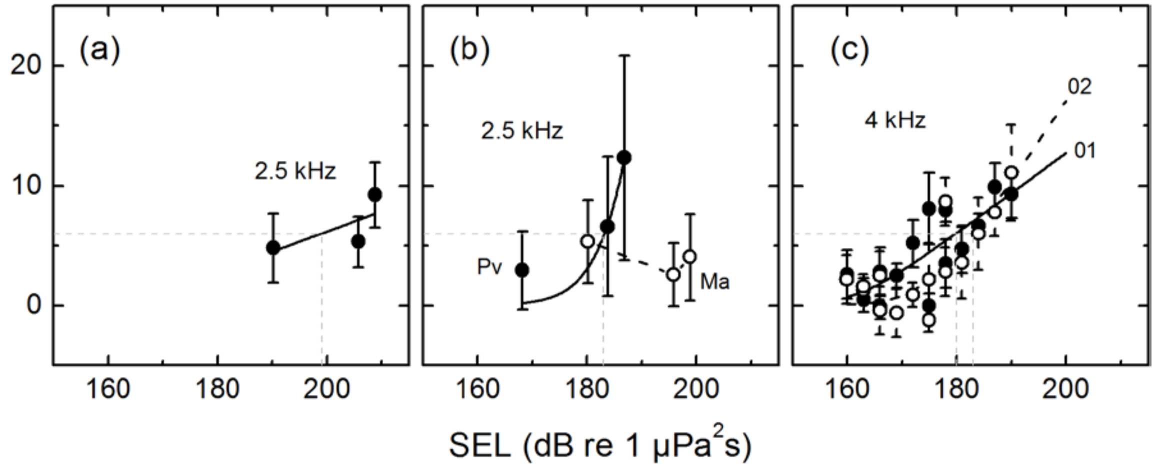

Figure A13. TTS growth data for pinnipeds obtained using behavioral methods. Growth curves were obtained by fitting Eq. (A10) to the TTS data as a function of SEL. Onset TTS was defined as the SEL value from the fitted curve at a TTS = 6 dB, for only those datasets that bracketed 6 dB of TTS. Frequency values within the panels indicate the exposure frequencies. Numeric values in panel (c) indicate subjects 01 and 02. Solid lines are fit to the filled symbols; dashed lines are fit to the open symbols. See Table A6 for explanation of the datasets in each panel.

Table A6. Summary of marine mammal TTS growth data and onset exposure levels. Only those data from which growth curves could be generated are included. TTS onset values are expressed in SEL, in dB re 1 μPa^2s. Tests featured continuous exposure to steady-state noise and behavioral threshold measurements unless otherwise indicated.

Group	Species	Subject	Freq. (kHz)	Min TTS (dB)	Max TTS (dB)	TTS Onset (dB SEL)	TTS growth rate (dB/dB)	PTS Onset (dB SEL)	TTS-PTS offset (dB)	Notes	Reference	Figure
MF	*Tursiops truncatus*	BEN	3	0	7	211*	0.21	—	—	TTS onset higher than subsequent test	(Finneran et al., 2005a)	10(a)
MF	*Tursiops truncatus*	NAY	3	0	5	—	0.13	—	—		(Finneran et al., 2005a)	10(b)
MF	*Tursiops truncatus*	BLU	3	4	11	207*	1.5	—	—	intermittent	(Finneran et al., 2010a)	10(c)
MF	*Tursiops truncatus*	BLU	3	0	23	206*	1.0	240	34	TTS onset higher than subsequent tests	(Finneran et al., 2010b)	10(d)
MF	*Tursiops truncatus*	TYH	3	0	9	194	0.35	—	—		(Finneran et al., 2010b)	10(e)
MF	*Tursiops truncatus*	BLU	3 7.1 10 14.1 20 28.3	0 0 1 0 0 0	13 7 13 22 25 30	190 184 179 176 181 177	0.28 0.21 0.48 0.95 1.2 4.5	— — — 213 212 190	— — — 37 31 13		(Finneran and Schlundt, 2013)	10(f) 10(f) 10(g) 10(g) 10(h) 10(h)
MF	*Tursiops truncatus*	TYH	40 56.6	0 0	11 12	182 181	0.46 1.1	— —	— —		(Finneran and Schlundt, 2013)	10(i) 10(i)
MF	*Delphinapterus leucas*	N/a	32	20	40	—	1.4	195	—	AEP	(Popov et al., 2011b)	11(a)

Group	Species	Subject	Freq. (kHz)	Min TTS (dB)	Max TTS (dB)	TTS Onset (dB SEL)	TTS growth rate (dB/dB)	PTS Onset (dB SEL)	TTS-PTS offset (dB)	Notes	Reference	Figure
MF	*Delphinapterus leucas*	female	11.2 22.5 45 90	25 38 9 21	50 63 51 31	— — — —	2.8 2.5 3.0 0.8	190 183 193 208	— — — —	AEP	(Popov et al., 2013)	11(b) 11(b) 11(c) 11(c)
MF	*Delphinapterus leucas*	male	11.2 22.5 45 90	15 28 13 8	48 55 42 24	— — — —	2.5 1.7 2.7 1.5	195 188 198 210	— — — —	AEP	(Popov et al., 2013)	11(d) 11(d) 11(e) 11(e)
MF	*Delphinapterus leucas*	female	22.5	0	40	184*	1.7	206	22	AEP	(Popov et al., 2014)	11(f)
MF	*Delphinapterus leucas*	male	22.5	12	40	—	1.2	197	—	AEP	(Popov et al., 2014)	11(f)
HF	*Phocoena phocoena*	02	4	2	15	165	0.3	—	—		(Kastelein et al., 2012a)	12(a)
HF	*Phocoena phocoena*	02	~1.5 ~1.5	0 0	32 7	191 197*	2.8 0.4	207 —	16 —	100% duty cycle 10% duty cycle	(Kastelein et al., 2014b)	12(b) 12(b)
HF	*Phocoena phocoena*	02	6.5 6.5	1 0	13 22	161 176*	0.3 1.3	— 204	— 28	6.5 kHz test freq. 9.2 kHz test freq.	(Kastelein et al., 2014a)	12(c) 12(c)
HF	*Phocoena phocoena*	02	~6.5 ~6.5	2 2	21 13	180* 182*	2.7 1.3	197 —	17 —	100% duty cycle 10% duty cycle	(Kastelein et al., 2015b)	12(d) 12(d)
HF	*Neophocaena phocaenoides*	male	22 32	28 25	35 45	— —	0.7 1.0	186 177	— —	AEP	(Popov et al., 2011a)	12(e)
HF	*Neophocaena phocaenoides*	female	45 90	23 18	30 25	— —	0.36 0.48	213 213	— —	AEP	(Popov et al., 2011a)	12(f)
HF	*Phocoena phocoena*	Eigil	impulse	0	20	162	**	—	—	AEP	(Lucke et al., 2009)	12(g)

Group	Species	Subject	Freq. (kHz)	Min TTS (dB)	Max TTS (dB)	TTS Onset (dB SEL)	TTS growth rate (dB/dB)	PTS Onset (dB SEL)	TTS-PTS offset (dB)	Notes	Reference	Figure
OW	*Zalophus californianus*	Rio	2.5	5	9	199	0.17	—	—		(Kastak et al., 2005)	13(a)
PW	*Phoca vitulina*	Sprouts	2.5	3	12	183	6.4	—	—		(Kastak et al., 2005)	13(b)
PW	*Mirounga angustirostris*	Burnyce	2.5	3	5	—	—	—	—		(Kastak et al., 2005)	13(b)
PW	*Phoca vitulina*	01	4	0	10	180	0.33	—	—		(Kastelein et al., 2012b)	13(c)
PW	*Phoca vitulina*	02	4	0	11	183*	0.68	—	—	TTS_{16}	(Kastelein et al., 2012b)	13(c)

* SELs not used in subsequent analyses to optimize ΔT or define K for TTS or PTS exposure functions. Reasons for exclusion include: (i) another data set resulted in a lower onset TTS at the same frequency, (ii) the data set featured a duty cycle less than 100%, (iii) TTS values were measured at times significantly larger than 4 min, (iv) data were obtained from AEP testing, or (v) a lower TTS onset was found at a different hearing test frequency (also see Notes).

** Distribution of data did not support an accurate estimate for growth rate (the standard error was four orders of magnitude larger than the slope estimate)

IX. TTS EXPOSURE FUNCTIONS FOR SONARS

Derivation of the weighting function parameters utilized the exposure function form described by Eq. (A2), so that the shapes of the functions could be directly compared to the TTS onset data (Table A6) when available. The function shapes were first determined via the parameters a, b, f_1, and f_2, then the gain constant K was determined for each group to provide the best fit to the TTS data or estimated TTS onset value at a particular frequency.

9.1 LOW- AND HIGH-FREQUENCY EXPONENTS (a, b)

The high-frequency exponent, b, was fixed at $b = 2$. This was done to match the previous value used in the Phase 2 functions, since no new TTS data are available at the higher frequencies and the equal latency data are highly variable at the higher frequencies.

The low-frequency exponent, a, was defined as $a = s_0/20$, where s_0 is the lower of the slope of the audiogram or equal latency curves (in dB/decade) at low frequencies (Table A5). This causes the weighting function slope to match the shallower slope of the audiogram or equal latency contours at low frequencies. In practice, the audiogram slopes were lower than the equal latency slopes for all groups except the mid-frequency cetaceans (group MF).

9.2 FREQUENCY CUTOFFS (f_1, f_2)

The frequency cutoffs f_1 and f_2 were defined as the frequencies below and above the frequency of best hearing (f_0, Table A5) where the composite audiogram thresholds values were ΔT-dB above the threshold at f_0 (Fig. A14). If $\Delta T = 0$, the weighting function shape would match the shape of the inverse audiogram. Values of $\Delta T > 0$ progressively “compress” the weighting function, compared to the audiogram, near the frequency region of best sensitivity. This compression process is included to match the marine mammal TTS data, which show less change in TTS onset with frequency than would be predicted by the audiogram in the region near best sensitivity.

To determine ΔT, the exposure function amplitude defined by Eq. (A2) was calculated for the mid- and high-frequency cetaceans using ΔT values that varied from 0 to 20 dB. For each ΔT value, the constant K was adjusted to minimize the mean-squared error between the function amplitude and the TTS data (Fig. A15). This process was performed using composite audiograms based on both the original and normalized threshold data. Fits were performed using only TTS data resulting from continuous exposures (100% duty cycle). If hearing was tested at multiple frequencies after exposure, the lowest TTS onset value was used.

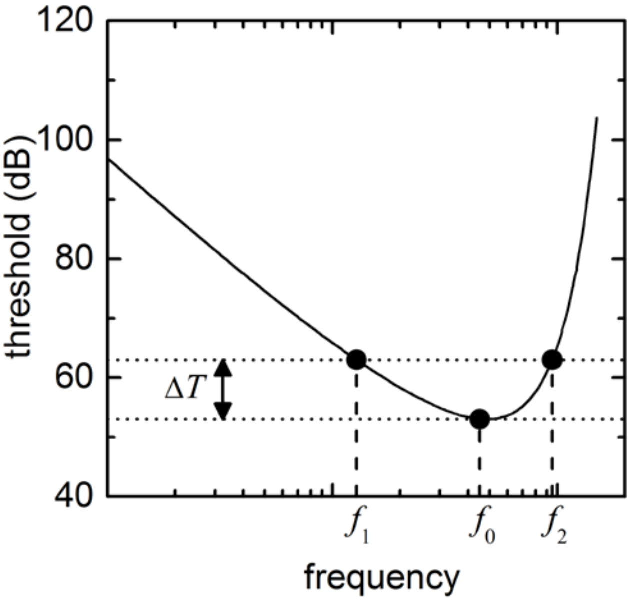

Figure A14. **The cutoff frequencies f_1 and f_2 were defined as the frequencies below and above f_0 at which the composite audiogram values were ΔT-dB above the threshold at f_0 (the lowest threshold).**

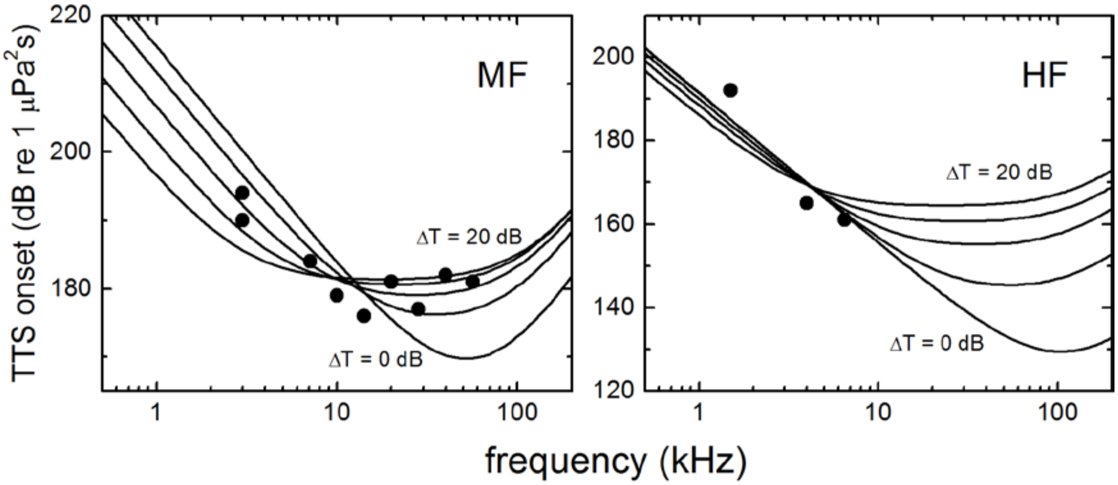

Figure A15. **Effect of ΔT adjustment on the TTS exposure functions for the mid-frequency cetaceans (left) and high-frequency cetaceans (right). To calculate the exposure functions, a and b were defined as $a = s_0/20$ and $b = 2$. ΔT was then varied from 0 to 20. At each value of ΔT, K was adjusted to minimize the squared error between the exposure function and the onset TTS data (symbols). As ΔT increases, f_1 decreases and f_2 increases, causing the pass-band of the function to increase and the function to "flatten".**

For the original and normalized data, the errors between the best-fit exposure functions and the TTS data for the MF and HF cetaceans were squared, summed, and divided by the total number of TTS data points (12). This provided an overall mean-squared error (MSE) for the original and normalized data as a function of ΔT (Fig. A16). The conditions (ΔT value and original/normalized threshold audiograms) resulting in the lowest MSE indicated the best fit of the exposure functions to the TTS data. For the MF and HF cetacean data, the lowest MSE occurred with the normalized threshold data with ΔT = 9 dB. **Therefore, f_1 and f_2 for the remaining species groups were defined using composite audiograms based on normalized thresholds with ΔT = 9 dB.**

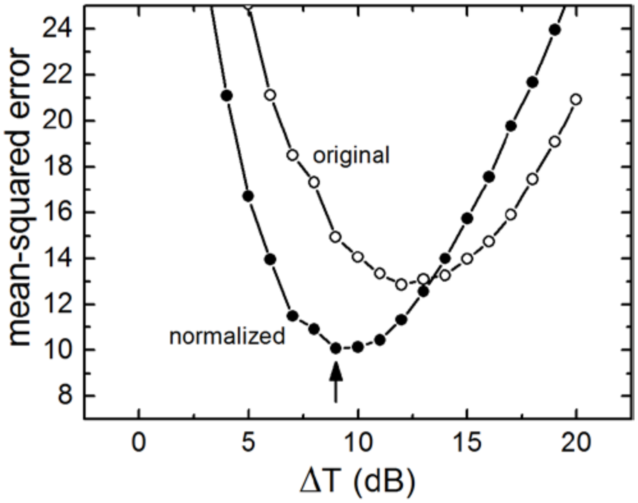

Figure A16. **Relationship between ΔT and the resulting mean-squared error (MSE) between the exposure functions and onset TTS data. The MSE was calculated by adding the squared errors between the exposure functions and TTS data for the MF and HF cetacean groups, then dividing by the total number of TTS data points. This process was performed using the composite audiograms based on original and normalized threshold data and ΔT values from 0 to 20. The lowest MSE value was obtained using the audiograms based on normalized thresholds with ΔT = 9 dB (arrow).**

9.3 GAIN PARAMETERS *K* AND *C*

The gain parameter *K* was defined to minimize the squared error between the exposure function and the TTS data for each species group. Note that *K* is not necessarily equal to the minimum value of the exposure function.

For the low-frequency cetaceans and sirenians, for which no TTS data exist, TTS onset at the frequency of best hearing (f_0) was estimated by assuming that, at the frequency of best hearing, the numeric difference between the auditory threshold (in dB SPL) and the onset of TTS (in dB SEL) would be similar to that observed in the other species groups. Table A7 summarizes the onset TTS and composite threshold data for the MF, HF, OW, and PW groups. For these groups, the median difference between the TTS onset and composite audiogram threshold at f_0 was 126 dB. In the absence of data, the hearing threshold at f_0 for the LF group was set equal to the median threshold at f_0 for the other groups (MF, HF, SI, OW, PW, median = 54 dB re 1 μPa). The TTS onset value at f_0 is therefore 180 dB re 1 μPa^2s for the low-frequency cetaceans (Table A7). For the sirenians, the lowest threshold was 61 dB re 1 µPa, making the onset TTS estimate 187 dB re 1 µPa^{2}s (Table A7).

Table A7. **Differences between composite threshold values (Fig. A5) and TTS onset values at the frequency of best hearing (f_0) for the in-water marine mammal species groups. The values for the low-frequency cetaceans and sirenians were estimated using the median difference (126) from the MF, HF, OW, and PW groups.**

Group	f_0 (kHz)	Threshold at f_0 (dB re 1 µPa)	TTS onset at f_0 (dB re 1 µPa^{2}s)	Difference	Estimated difference	Estimated TTS onset at f_0 (dB re 1 µPa^{2}s)
LF	5.6	54			126	180
MF	55	54	179	125		
HF	105	48	156	108		
SI	16	61			126	187
OW	12	67	199	132		
PW	8.6	53	181	128		

Once *K* was determined, the weighted threshold for onset TTS was determined from the minimum value of the exposure function. Finally, the constant *C* was determined by substituting parameters *a*, *b*, f_1, and f_2 into Eq. (A1), then adjusting *C* so the maximum amplitude of the weighting function was 0 dB; this is equivalent to the difference between the weighted TTS threshold and *K* [see Eqs. (A3)–(A8)].

Table A8 summarizes the various function parameters, the weighted TTS thresholds, and the goodness of fit values between the TTS exposure functions and the onset TTS data. The various TTS exposure functions are presented in Figs. A17–A20.

Table A8. **Weighting function and TTS exposure function parameters for use in Eqs. (A1) and (A2) for steady-state exposures. R^2 values represent goodness of fit between exposure function and TTS onset data (Table A6).**

Group	a	b	f_1 (kHz)	f_2 (kHz)	K (dB)	C (dB)	Weighted TTS threshold (dB SEL)	R^2
LF	1	2	0.20	19	179	0.13	179	—
MF	1.6	2	8.8	110	177	1.20	178	0.825
HF	1.8	2	12	140	152	1.36	153	0.864
SI	1.8	2	4.3	25	183	2.62	186	—
OW	2	2	0.94	25	198	0.64	199	—
PW	1	2	1.9	30	180	0.75	181	0.557

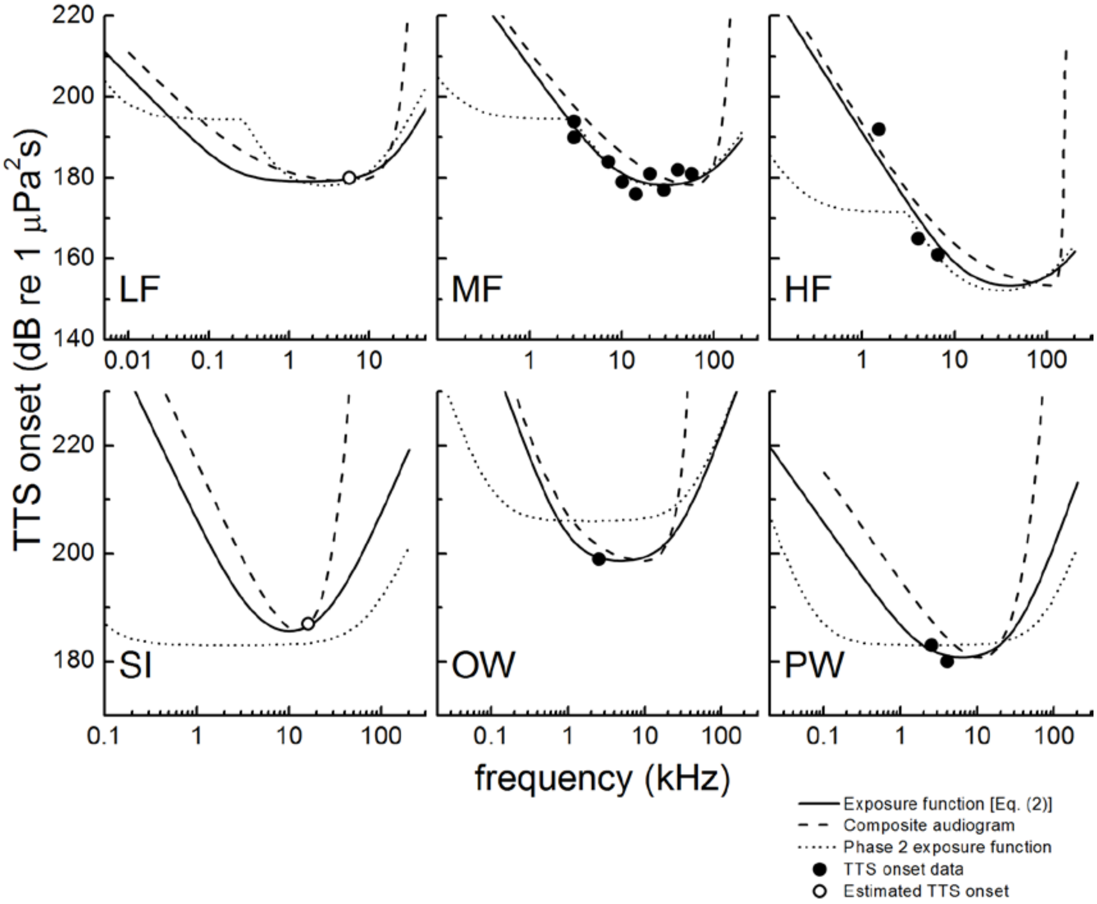

Figure A17. Exposure functions (solid lines) generated from Eq. (A2) with the parameters specified in Table A7. Dashed lines — (normalized) composite audiograms used for definition of parameters *a*, f_1, and f_2. A constant value was added to each audiogram to equate the minimum audiogram value with the exposure function minimum. Short dashed line — Navy Phase 2 exposure functions for TTS onset for each group. Filled symbols — onset TTS exposure data (in dB SEL) used to define exposure function shape and vertical position. Open symbols — estimated TTS onset for species for which no TTS data exist.

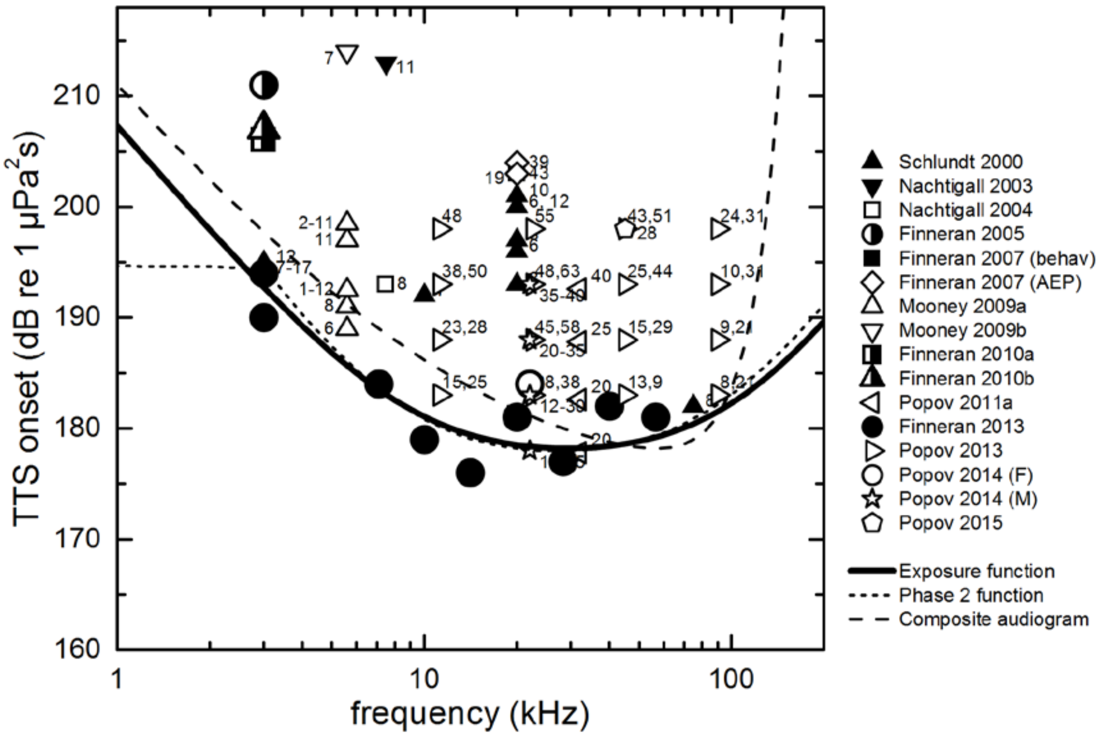

Figure A18. **Mid-frequency cetacean exposure function, (normalized) composite audiogram, and Phase 2 exposure functions compared to mid-frequency cetacean TTS data. Large symbols with no numeric values indicate onset TTS exposures. Smaller symbols represent specific amounts of TTS observed, with numeric values giving the amount (or range) or measured TTS. Filled and half-filled symbols — behavioral data. Open symbols — AEP data.**

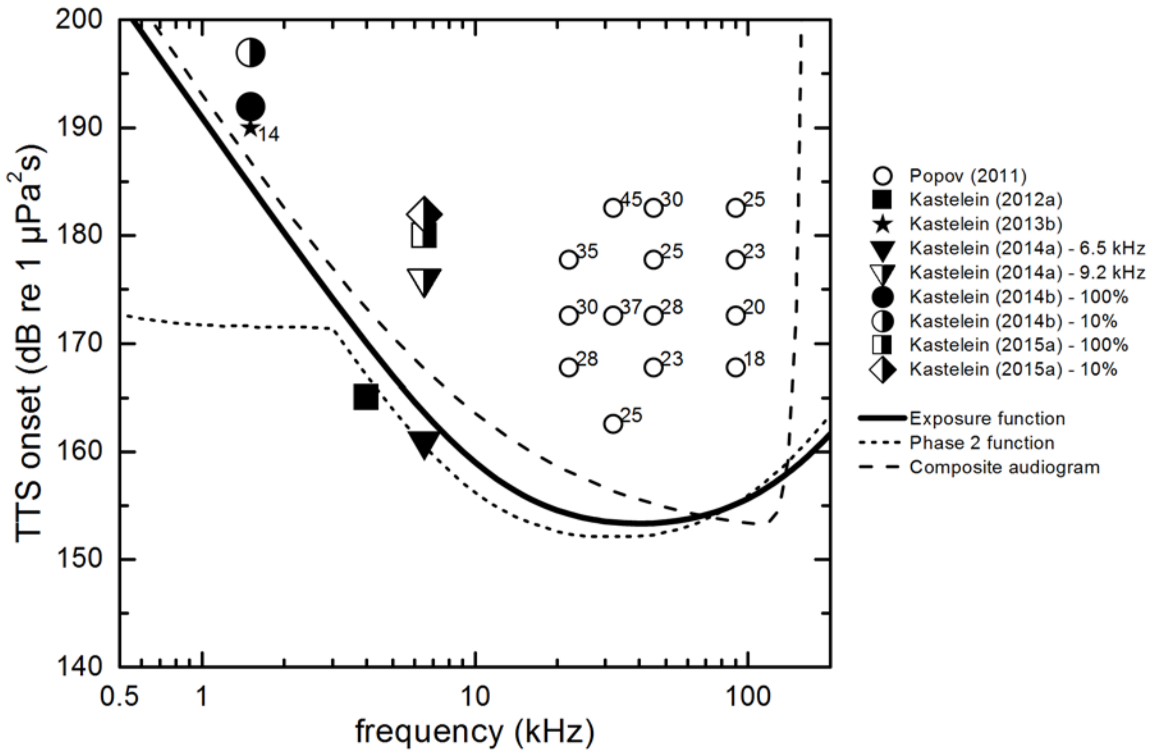

Figure A19. **High-frequency cetacean TTS exposure function, (normalized) composite audiogram, and Phase 2 exposure functions compared to high-frequency cetacean TTS data. Large symbols with no numeric values indicate onset TTS exposures. Smaller symbols represent specific amounts of TTS observed, with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

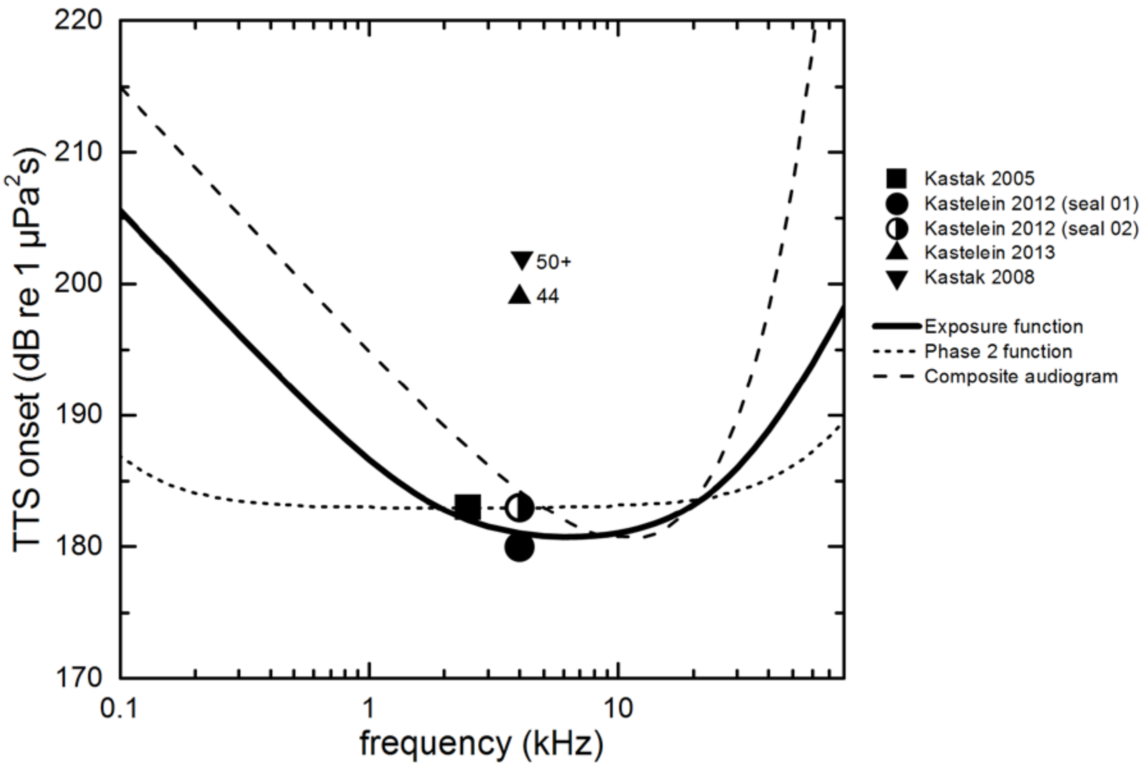

Figure A20. Phocid (underwater) exposure function, (normalized) composite audiogram, and Phase 2 exposure functions compared to phocid TTS data. Large symbols with no numeric values indicate onset TTS exposures. Smaller symbols represent specific amounts of TTS observed, with numeric values giving the amount (or range) or measured TTS.

X. PTS EXPOSURE FUNCTIONS FOR SONARS

As in previous acoustic effects analyses (Southall et al., 2007; Finneran and Jenkins, 2012), the shape of the PTS exposure function for each species group is assumed to be identical to the TTS exposure function for that group. Thus, definition of the PTS function only requires the value for the constant *K* to be determined. This equates to identifying the increase in noise exposure between the onset of TTS and the onset of PTS.

For Phase 2, Navy used a 20-dB difference between TTS onset and PTS onset for cetaceans and a 14-dB difference for phocids, otariids, odobenids, mustelids, ursids, and sirenians (Finneran and Jenkins, 2012). The 20-dB value was based on human data (Ward et al., 1958) and the available marine mammal data, essentially following the extrapolation process proposed by Southall et al. (2007). The 14-dB value was based on a 2.5 dB/dB growth rate reported by Kastak et al. (2007) for a California sea lion tested in air.

For Phase 3, a difference of 20 dB between TTS onset and PTS onset is used for all species groups. This is based on estimates of exposure levels actually required for PTS (i.e., 40 dB of TTS) from the marine mammal TTS growth curves (Table 6), which show differences of 13 to 37 dB (mean = 24, median = 22, *n* = 9) between TTS onset and PTS onset in marine mammals. These data show most differences between TTS onset and PTS onset are larger than 20 dB and all but one value are larger than 14 dB.

The value of *K* for each PTS exposure function and the weighted PTS threshold are therefore determined by adding 20 dB to the *K*-value for the TTS exposure function or the TTS weighted threshold, respectively (see Table A10).

XI. TTS/PTS EXPOSURE FUNCTIONS FOR EXPLOSIVES

The shapes of the TTS and PTS exposure functions for explosives and other impulsive sources are identical to those used for sonars and other active acoustic sources (i.e., steady-state or non-impulsive noise sources). Thus, defining the TTS and PTS functions only requires the values for the constant K to be determined.

Phase 3 analyses for TTS and PTS from underwater detonations and other impulsive sources follow the approach proposed by Southall et al. (2007) and used in Phase 2 analyses (Finneran and Jenkins, 2012), where a weighted SEL threshold is used in conjunction with an unweighted peak SPL threshold. The threshold producing the greater range for effect is used for estimating the effects of the noise exposure.

Peak SPL and SEL thresholds for TTS were based on TTS data from impulsive sound exposures that produced 6 dB or more TTS for the mid- and high-frequency cetaceans (the only groups for which data are available). The peak SPL thresholds were taken directly from the literature: 224 and 196 dB re 1 μPa, for the mid- and high-frequency cetaceans, respectively (Table A9). The SEL-based thresholds were determined by applying the Phase 3 weighting functions for the appropriate species groups to the exposure waveforms that produced TTS, then calculating the resulting weighted SELs. When this method is applied to the exposure data from Finneran et al. (2002) and Lucke et al. (2009), the SEL-based weighted TTS thresholds are 170 and 140 dB re 1 μPa^2s for the mid- and high-frequency cetaceans, respectively (Table A9). Note that the data from Lucke et al. (2009) are based on AEP measurements and may thus under-estimate TTS onset; however, they are used here because of the very limited nature of the impulse TTS data for marine mammals and the likelihood that the high-frequency cetaceans are more susceptible than the mid-frequency cetaceans (i.e., use of the mid-frequency cetacean value is not appropriate). Based on the limited available data, it is reasonable to assume that the exposures described by Lucke et al. (2009), which produced AEP-measured TTS of up to 20 dB, would have resulted in a behavioral TTS of at least 6 dB.

The harbor porpoise data from Kastelein et al. (2015c) were not used to derive the high-frequency cetacean TTS threshold, since the largest observed TTS was only 4 dB. However, these data provide an opportunity to check the TTS onset proposed for the high-frequency cetacean group. Kastelein et al. (2015c) provide a representative frequency spectrum for a single, simulated pile driving strike at a specific measurement location. When the high-frequency cetacean weighting function is applied to this spectrum and the 1/3-octave SELs combined across frequency, the total weighted SEL for a single strike is found to be 114 dB re 1 μPa^2s. For 2760 impulses, the cumulative, weighted SEL would then be 148 dB re 1 μPa^2s. The average SEL in the pool was reported to be 9 dB lower than the SEL at the measurement position, thus the average, cumulative weighted SEL would be approximately 139 dB re 1 μPa^2s, which compares favorably to the high-frequency cetacean TTS threshold of 140 dB re 1 μPa^2s derived from the Lucke et al. (2009) air gun data.

For species groups for which no impulse TTS data exist, the weighted SEL thresholds were estimated using the relationship between the steady-state TTS weighted threshold and the impulse TTS weighted threshold for the groups for which data exist (the mid- and high-frequency cetaceans):

$$G_s - G_i = \overline{C}_s - \overline{C}_i, \tag{A11}$$

where G indicates thresholds for a species group for which impulse TTS data are not available, $\overline{C}$ indicates the median threshold for the groups for which data exist, the subscript s indicates a steady-state threshold, and the subscript i indicates an impulse threshold (note that since data are only available for the mid- and high-frequency cetaceans the median and mean are identical). Equation (A11) is equivalent to the relationship used by Southall et al. (2007), who expressed the relationship as $\overline{C}_s - G_s = \overline{C}_i - G_i$. For the mid- and high-frequency cetaceans, the steady-state TTS thresholds are 178 and 153 dB re 1 μPa^{2}s, respectively, and the impulse TTS thresholds are 170 and 140 dB re 1 μPa^{2}s, respectively, making $\overline{C}_s - \overline{C}_i$ = 11 dB. Therefore, for each of the remaining groups the SEL-based impulse TTS threshold is 11 dB below the steady-state TTS threshold (Table A9).

To estimate peak SPL-based thresholds, Southall et al. (2007) used Eq. (A11) with peak-SPL values for the impulse thresholds and SEL-based values for the steady-state thresholds. For the mid- and high-frequency cetaceans, the steady-state (SEL) TTS thresholds are 178 and 153 dB re 1 μPa^{2}s, respectively, and the peak SPL, impulse TTS thresholds are 224 and 196 dB re 1 μPa, respectively, making $\overline{C}_s - \overline{C}_i$ = -44 dB. Based on this relationship, the peak SPL-based impulse TTS threshold (in dB re 1 μPa) would be 44 dB above the steady-state TTS threshold (in dB re 1 μPa^{2}s), making the peak SPL thresholds vary from 222 to 243 dB re 1 μPa. Given the limited nature of the underlying data, and the relatively high values for some of these predictions, for Phase 3 analyses impulsive peak SPL thresholds are estimated using a “dynamic range” estimate based on the difference (in dB) between the impulsive noise, peak SPL TTS onset (in dB re 1 μPa) and the hearing threshold at f_0 (in dB re 1 μPa) for the groups for which data are available (the mid- and high-frequency cetaceans). For the mid-frequency cetaceans, the hearing threshold at f_0 is 54 dB re 1 μPa and the peak SPL TTS threshold is 224 dB re 1 μPa, resulting in a dynamic range of 170 dB. For the high-frequency cetaceans, the hearing threshold at f_0 is 48 dB re 1 μPa and the peak SPL-based TTS threshold is 196 dB re 1 μPa, resulting in a dynamic range of 148 dB. The median dynamic range for the mid- and high-frequency cetaceans is therefore 159 dB (since there are only two values, the mean and median are equal). For the remaining species groups, the impulsive peak SPL-based TTS thresholds are estimated by adding 159 dB to the hearing threshold at f_0 (Table A9).

Since marine mammal PTS data from impulsive noise exposures do not exist, onset-PTS levels for impulsive exposures were estimated by adding 15 dB to the SEL-based TTS threshold and adding 6 dB to the peak pressure based thresholds. These relationships were derived by Southall et al. (2007) from impulse noise TTS growth rates in chinchillas. The appropriate frequency weighting function for each functional hearing group is applied only when using the SEL-based thresholds to predict PTS.

Table A9. **TTS and PTS thresholds for explosives and other impulsive sources. SEL thresholds are in dB re 1 μPa^{2}s and peak SPL thresholds are in dB re 1 μPa.**

Group	Hearing threshold at f_0	TTS threshold		PTS threshold	
	SPL (dB SPL)	SEL (weighted) (dB SEL)	peak SPL (dB SPL)	SEL (weighted) (dB SEL)	peak SPL (dB SPL)
LF	54	168	213	183	219
MF	54	170	224	185	230
HF	48	140	196	155	202
SI	61	175	220	190	226
OW	67	188	226	203	232
PW	53	170	212	185	218

XII. SUMMARY

Figure A21 illustrates the shapes of the various Phase 3 auditory weighting functions. Table A10 summarizes the parameters necessary to calculate the weighting function amplitudes using Eq. (A1).

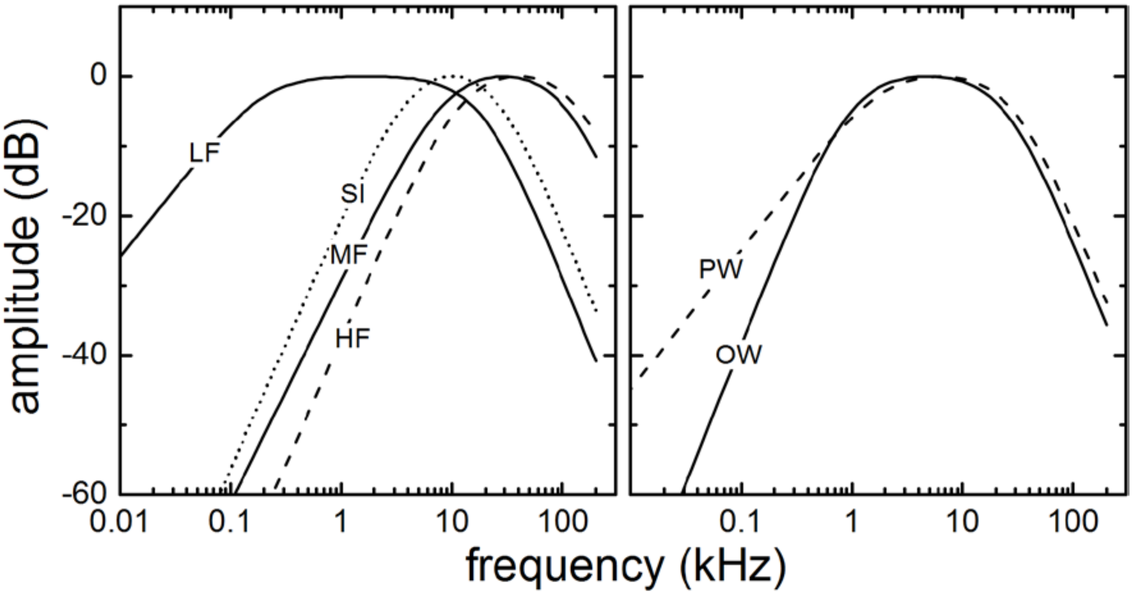

Figure A21. Navy Phase 3 weighting functions for marine mammal species groups exposed to underwater sound. Parameters required to generate the functions are provided in Table A10.

Table A10. Summary of weighting function parameters and TTS/PTS thresholds. SEL thresholds are in dB re 1 µPa^{2}s and peak SPL thresholds are in dB re 1 µPa.

$W(f)=C+10\log_{10}\left\{\frac{(f/f_1)^{2a}}{\left[1+(f/f_1)^2\right]^a\left[1+(f\right.}\right.$						Non-impulsive		Impulse			
						TTS threshold	PTS threshold	TTS threshold		PTS threshold	
Group	*a*	*b*	*f₁* (kHz)	*f₂* (kHz)	*C* (dB)	SEL (weighted)	SEL (weighted)	SEL (weighted)	peak SPL (unweighted)	SEL (weighted)	peak SPL (unweighted)
LF	1	2	0.20	19	0.13	179	199	168	213	183	219
MF	1.6	2	8.8	110	1.20	178	198	170	224	185	230
HF	1.8	2	12	140	1.36	153	173	140	196	155	202
SI	1.8	2	4.3	25	2.62	186	206	175	220	190	226
OW	2	2	0.94	25	0.64	199	219	188	226	203	232
PW	1	2	1.9	30	0.75	181	201	170	212	185	218

To properly compare the TTS/PTS criteria and thresholds used by Navy for Phase 2 and Phase 3, both the weighting function shape and weighted threshold values must be taken into account; the weighted thresholds by themselves only indicate the TTS/PTS threshold at the most susceptible frequency (based on the relevant weighting function). Since the exposure functions incorporate both the shape of the weighting function and the weighted threshold value, they provide the best means of comparing the frequency-dependent TTS/PTS thresholds for Phase 2 and 3 (Figs A22 and A23).

The most significant differences between the Phase 2 and Phase 3 functions include the following:

(1) Thresholds at low frequencies are generally higher for Phase 3 compared to Phase 2. This is because the Phase 2 weighting functions utilized the "M-weighting" functions (Southall et al., 2007) at lower frequencies, where no TTS existed at that time. Since derivation of the Phase 2 thresholds, additional data have been collected (e.g., Kastelein et al., 2012a; Kastelein et al., 2013b; Kastelein et al., 2014b) to support the use of exposure functions that continue to increase at frequencies below the region of best sensitivity, similar to the behavior of mammalian audiograms and human auditory weighting functions.

(2) In the frequency region near best hearing sensitivity, the Phase 3 underwater thresholds for otariids and other marine carnivores (group OW) are lower than those used in Phase 2. In Phase 2, the TTS onset for the otariids was taken directly from the published literature (Kastak et al., 2005); for Phase 3, the actual TTS data from Kastak et al. (2005) were fit by a TTS growth curve using identical methods as those used with the other species groups.

(3) Impulsive TTS/PTS thresholds near the region of best hearing sensitivity are lower for Phase 3 compared to Phase 2.

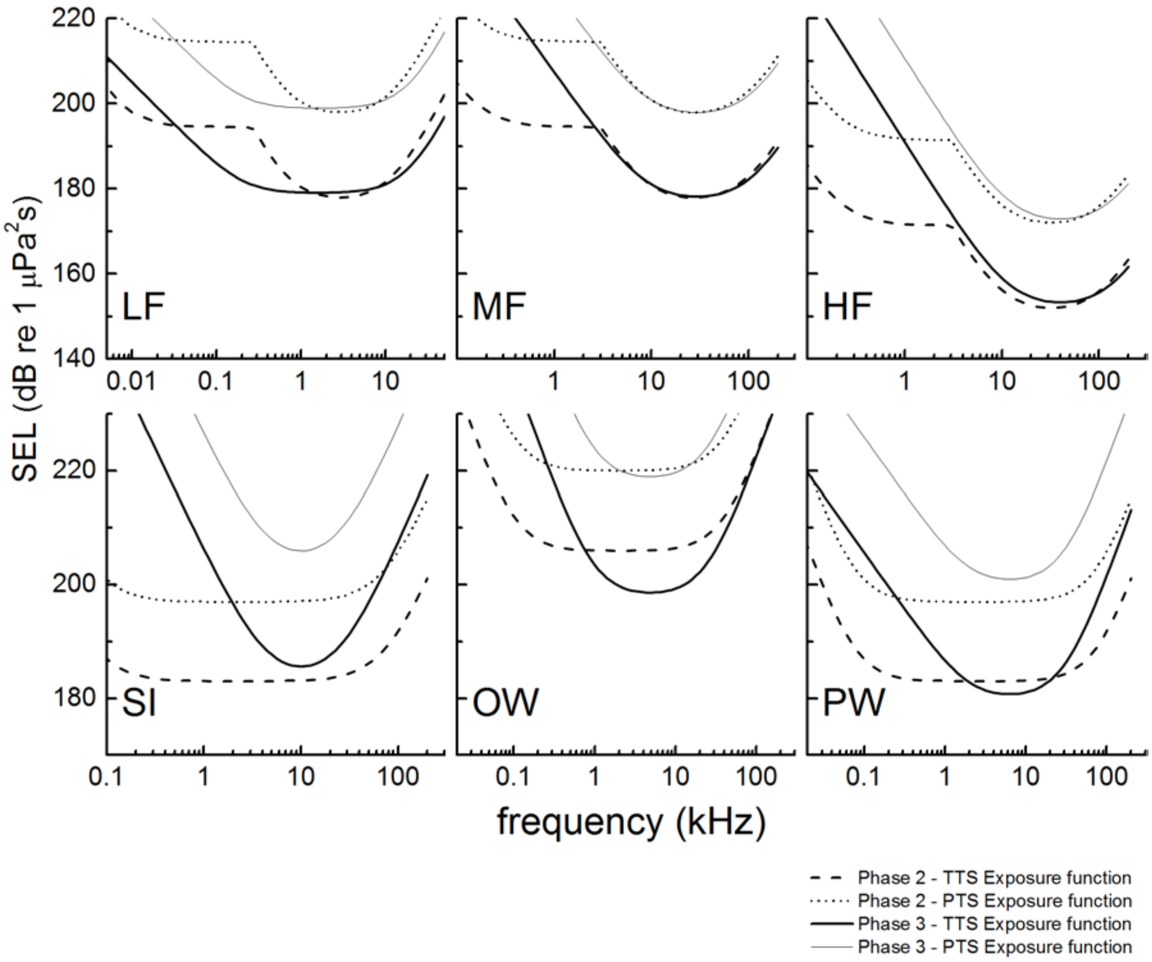

Figure A22. **TTS and PTS exposure functions for sonars and other (non-impulsive) active acoustic sources. Heavy solid lines — Navy Phase 3 TTS exposure functions (Table A10). Thin solid lines — Navy Phase 3 PTS exposure functions for TTS (Table A10). Dashed lines — Navy Phase 2 TTS exposure functions. Short dashed lines — Navy Phase 2 PTS exposure functions.**

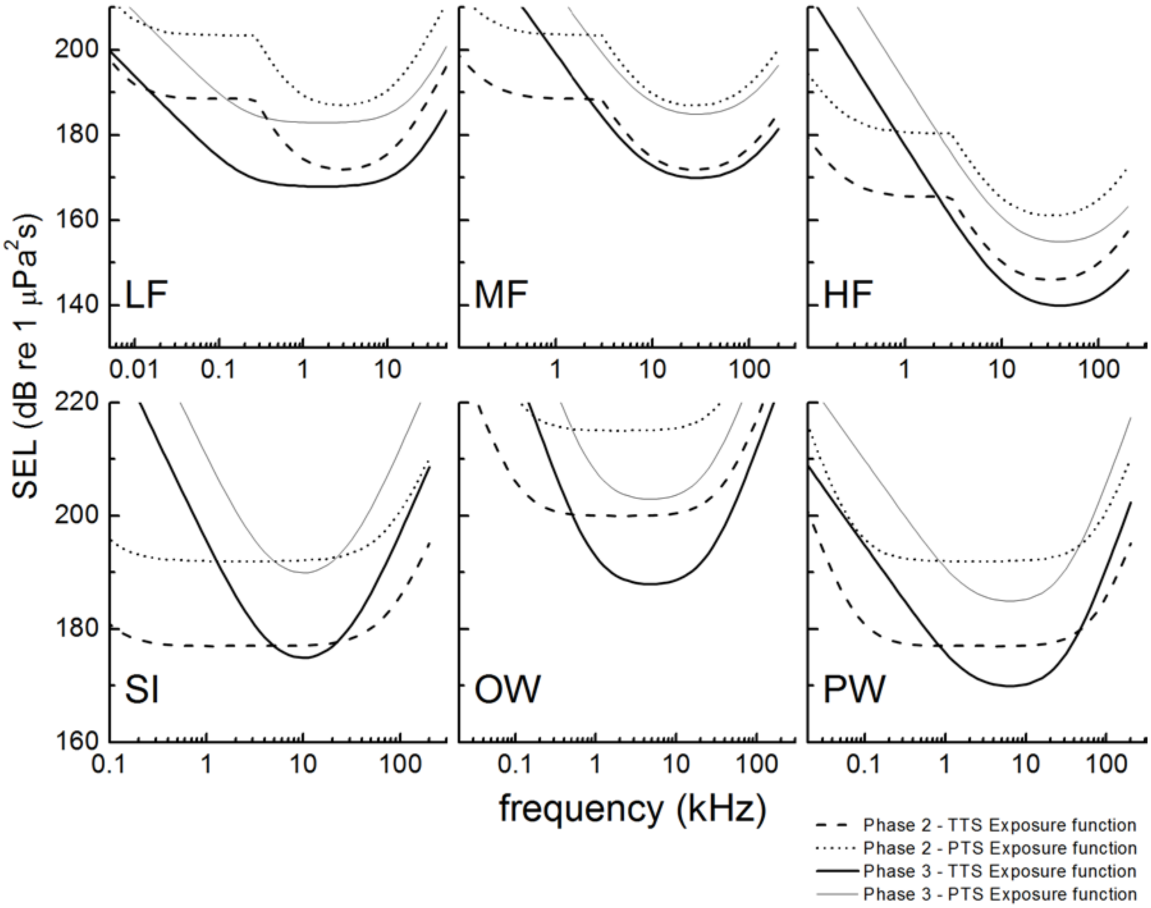

Figure A23. TTS and PTS exposure functions for explosives, impact pile driving, air guns, and other impulsive sources. Heavy solid lines — Navy Phase 3 TTS exposure functions (Table A10). Thin solid lines — Navy Phase 3 PTS exposure functions for TTS (Table A10). Dashed lines — Navy Phase 2 TTS exposure functions. Short dashed lines — Navy Phase 2 PTS exposure functions.

APPENDIX A1. ESTIMATING A LOW-FREQUENCY CETACEAN AUDIOGRAM

A1.1. BACKGROUND

Psychophysical and/or electrophysiological auditory threshold data exist for at least one species within each hearing group, except for the low-frequency (LF) cetacean (i.e., mysticete) group, for which no direct measures of auditory threshold have been made. For this reason, an alternative approach was necessary to estimate the composite audiogram for the LF cetacean group.

The published data sources available for use in estimating mysticete hearing thresholds consist of: cochlear frequency-place maps created from anatomical measurements of basilar membrane dimensions (e.g., Ketten, 1994; Parks et al., 2007); scaling relationships between inter-aural time differences and upper-frequency limits of hearing (see Ketten, 2000); finite element models of head-related and middle-ear transfer functions (Tubelli et al., 2012; Cranford and Krysl, 2015); a relative hearing sensitivity curve derived by integrating cat and human threshold data with a frequency-place map for the humpback whale (Houser et al., 2001); and measurements of the source levels and frequency content of mysticete vocalizations (see review by Tyack and Clark, 2000). These available data sources are applied here to estimate a mysticete composite audiogram. Given that these data are limited in several regards and are quite different from the type of data supporting composite audiograms in other species, additional sources of information, such as audiograms from other marine mammals, are also considered and applied to make conservative extrapolations at certain decision points.

Mathematical models based on anatomical data have been used to predict hearing curves for several mysticete species (e.g., Ketten and Mountain, 2009; Cranford and Krysl, 2015). However, these predictions are not directly used to derive the composite audiogram for LF cetaceans for two primary reasons:

> (1) There are no peer-reviewed publications that provide a complete description of the mathematical process by which frequency-place maps based on anatomical measurements were integrated with models of middle-ear transfer functions and/or other information to derive the predicted audiograms presented in several settings by Ketten/Mountain (e.g., Ketten and Mountain, 2009). As a result, the validity of the resulting predicted audiograms cannot be independently evaluated, and these data cannot be used in the present effort.
>
> (2) Exclusion of the Ketten/Mountain predicted audiograms leaves only the Cranford/Krysl predicted fin whale hearing curve (Cranford and Krysl, 2015). However, this curve cannot be used by itself to predict hearing thresholds for all mysticetes because:
>
> (a) The Cranford/Krysl model is based on sound transmission through the head to the ear of the fin whale, but does not include the sensory receptors of the cochlea. There is therefore no way to properly predict the upper cutoff of

hearing and the shape of the audiogram at frequencies above the region of best predicted sensitivity.

(b) The audiogram does not possess the typical shape one would expect for an individual with normal hearing based on measurements from other mammals. Specifically, the "hump" in the low-frequency region and the shallow roll-off at high frequencies do not match patterns typically seen in audiometric data from other mammals with normal hearing. Given these considerations, the proposed audiogram cannot be considered representative of all mysticetes without other supporting evidence. Although the specific numeric thresholds from Cranford and Krysl (2015) are not directly used in the revised approach explained here, the predicted thresholds are still used to inform the LF cetacean composite audiogram derivation.

Vocalization data also cannot be used to directly estimate auditory sensitivity and audible range, since there are many examples of mammals that vocalize below the frequency range where they have best hearing sensitivity, and well below their upper hearing limit. However, it is generally expected that animals have at least some degree of overlap between the auditory sensitivity curve and the predominant frequencies present in conspecific communication signals. Therefore vocalization data can be used to evaluate, at least at a general level, whether the composite audiogram is reasonable; i.e., to ensure that the predicted thresholds make sense given what we know about animal vocalization frequencies, source levels, and communication range.

The realities of the currently available data leave only a limited amount of anatomical data and finite element modeling results to guide the derivation of the LF cetacean composite audiogram, supplemented with extrapolations from the other marine mammal species groups where necessary and a broad evaluation of the resulting audiogram in the context of whale bioacoustics.

A1.2. AUDIOGRAM FUNCTIONAL FORM AND REQUIRED PARAMETERS

Navy Phase 3 composite audiograms are defined by the equation

$$T(f) = T_0 + A\log_{10}\left(1 + \frac{F_1}{f}\right) + \left(\frac{f}{F_2}\right)^B, \qquad \text{(A1.1)}$$

where $T(f)$ is the threshold at frequency f, and T_0, F_1, F_2, A, and B are constants. To understand the physical significance and influence of the parameters T_0, F_1, F_2, A, and B, Eq. (A1.1) may be viewed as the sum of three individual terms:

$$T(f) = T_0 + L(f) + H(f), \qquad \text{(A1.2)}$$

where

$$L(f) = A\log_{10}\left(1 + \frac{F_1}{f}\right), \tag{A1.3}$$

and

$$H(f) = \left(\frac{f}{F_2}\right)^B . \tag{A1.4}$$

The first term, T_0, controls the vertical position of the curve; i.e., T_0 shifts the audiogram up and down.

The second term, $L(f)$, controls the low-frequency behavior of the audiogram. At low frequencies, when $f < F_1$, Eq. (A1.3) approaches

$$L(f) = A\log_{10}\left(\frac{F_1}{f}\right), \tag{A1.5}$$

which can also be written as

$$L(f) = A\log_{10} F_1 - A\log_{10} f . \tag{A1.6}$$

Equation (A.6) has the form of $y(x) = b - Ax$, where $x = \log_{10} f$; i.e., Eq. (A.6) describes a linear function of the logarithm of frequency. This means that, as frequency gets smaller and smaller, Eq. (A.3) — the low-frequency portion of the audiogram function — approaches a linear function with the logarithm of frequency, and has a slope of $-A$ dB/decade. As frequency increases towards F_1, $L(f)$ asymptotically approaches zero.

The third term, $H(f)$, controls the high-frequency behavior of the audiogram. At low frequencies, when $f << F_2$, Eq. (A1.4) has a value of zero. As f increases, $H(f)$ exponentially grows. The parameter F_2 defines the frequency at which the thresholds begin to exponentially increase, while the factor B controls the rate at which thresholds increase. Increasing F_2 will move the upper cutoff frequency to the right (to higher frequencies). Increasing B will increase the “sharpness” of the high-frequency increase.

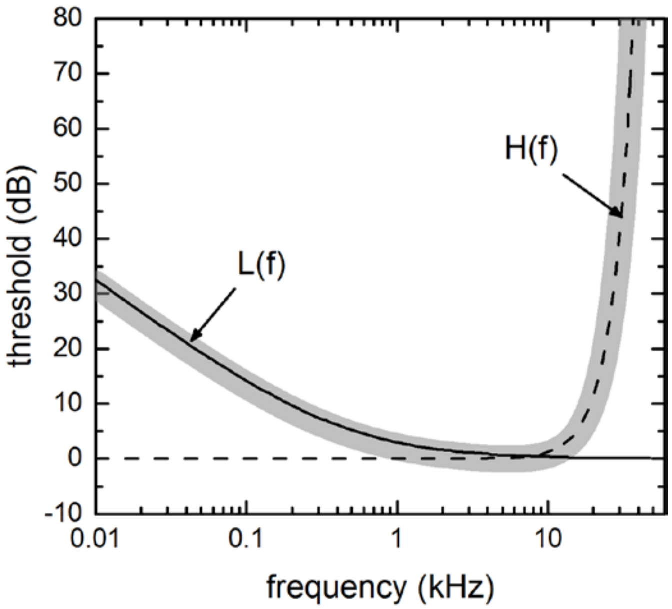

FIGURE A1.1. **Relationship between estimated threshold, T(f), (thick, gray line), low-frequency term, L(f), (solid line), and high-frequency term, H(f), (dashed line).**

A1.3. ESTIMATING AUDIOGRAM PARAMETERS

To derive a composite mysticete audiogram using Eq. (A1.1), the values of T_0, F_1, F_2, A, and B must be defined. The value for T_0 is determined by either adjusting T_0 to place the lowest threshold value to zero (to obtain a normalized audiogram), or to place the lowest expected threshold at a specific SPL (in dB re 1 μPa). For Navy Phase 3 analyses, the lowest LF cetacean threshold is defined to match the median threshold of the in-water marine mammal species groups (MF cetaceans, HF cetaceans, sirenians, otariids and other marine carnivores in water, and phocids in water; median = 54 dB re 1 μPa). The choices for the other parameters are informed by the published information regarding mysticete hearing.

The constant A is defined by assuming a value for the low-frequency slope of the audiogram, in dB/decade. Most mammals for which thresholds have been measured have low-frequency slopes ~30 to 40 dB/decade. However, finite element models of middle ear function in fin whales (Cranford and Krysl, 2015) and minke whales (Tubelli et al., 2012) suggest lower slopes, of ~25 or 20 dB/decade, respectively. **We therefore conservatively assume that A = 20 dB/decade.**

To define F_1, we first define the variable T' as the maximum threshold tolerance within the frequency region of best sensitivity (i.e., within the frequency range of best sensitivity, thresholds are within T' dB of the lowest threshold). Further, let f' be the lower frequency bound of the region of best sensitivity. When $f = f'$, $L(f) = T'$, and Eq. (A1.3) can then be solved for F_1 as a function of f', T', and A:

$$F_1 = f'\left(10^{T'/A} - 1\right). \quad \text{(A1.7)}$$

Anatomically-based models of mysticete hearing have resulted in various estimates for audible frequency ranges and frequencies of best sensitivity. Houser et al. (2001) estimated best sensitivity in humpback whales to occur in the range of 2 to 6 kHz, with thresholds within 3 dB of best sensitivity from ~1.4 to 7.8 kHz. For right whales, Parks et al. (2007) estimated the audible frequency range to be 10 Hz to 22 kHz. For minke whales, Tubelli et al. (2012) estimated the most sensitive hearing range, defined as the region with thresholds within 40 dB of best sensitivity, to extend from 30 to 100 Hz up to 7.5 to 25 kHz, depending on the specific model used. Cranford and Krysl (2015) predicted best sensitivity in fin whales to occur at 1.2 kHz, with thresholds within 3-dB of best sensitivity from ~1 to 1.5 kHz. Together, these model results broadly suggest best sensitivity (thresholds within ~3 dB of the lowest threshold) from ~1 to 8 kHz, and thresholds within ~40 dB of best sensitivity as low as ~30 Hz and up to ~25 kHz.

Based on this information, we assume LF cetacean thresholds are within 3 dB of the lowest threshold over a frequency range of 1 to 8 kHz, therefore $T' = 3$ dB and $f' = 1$ kHz, resulting in **F_1 = 0.41 kHz** [Eq. (A1.7)]. In other words, we define F_1 so that thresholds are ≤ 3 dB relative to the lowest threshold when the frequency is within the region of best sensitivity (1 to 8 kHz).

To define the high-frequency portion of the audiogram, the values of B and F_2 must be estimated. To estimate B for LF cetaceans, we take the median of the B values from the composite audiograms for the other in-water marine mammal species groups (MF cetaceans, HF cetaceans, sirenians, otariids and other marine carnivores in water, and phocids in water). **This results in $B = 3.2$ for the LF cetaceans.** Once B is defined, F_2 is adjusted to achieve a threshold value at 30 kHz of 40 dB relative to the lowest threshold. **This results in F_2 = 9.4 kHz. Finally, T_0 is adjusted to set the lowest threshold value to 0 dB for the normalized curve, or 54 dB re 1 μPa for the non-normalized curve; this results in T_0 = -0.81 and 53.19 for the normalized and non-normalized curves, respectively.**

The resulting composite audiogram is shown in Fig. A1.2. For comparison, predicted audiograms for the fin whale (Cranford and Krysl, 2015), and humpback whale (Houser et al., 2001) are included. The LF cetacean composite audiogram has lowest threshold at 5.6 kHz, but the audiogram is fairly shallow in the region of best sensitivity, and thresholds are within 1 dB of the lowest threshold from ~1.8 to 11 kHz, and within 3 dB of the lowest threshold from ~0.75 to 14 kHz. Low-frequency (< ~500 Hz) thresholds are considerably lower than those predicted by Cranford and Krysl (2015). High-frequency thresholds are also substantially lower than those predicted for the fin whale, with thresholds at 30 kHz only 40 dB above best hearing thresholds, and those at 40 kHz approximately 90 dB above best threshold. The resulting LF composite audiogram appears reasonable in a general sense relative the predominant frequencies present in mysticete conspecific vocal communication signals. While some species (e.g., blue whales) produce some extremely low (e.g., 10 Hz) frequency call components, the majority of mysticete social calls occur in the few tens of Hz to few kHz range, overlapping reasonably well with the predicted auditory sensitivity shown in the composite audiogram (within ~0 to 30 dB of predicted best sensitivity). A general pattern of some social calls containing energy shifted below the region of best hearing sensitivity is well-documented in other low-frequency species including many phocid seals (see Wartzok and Ketten, 1999) and some terrestrial mammals, notably the Indian elephant (Heffner and Heffner, 1982).

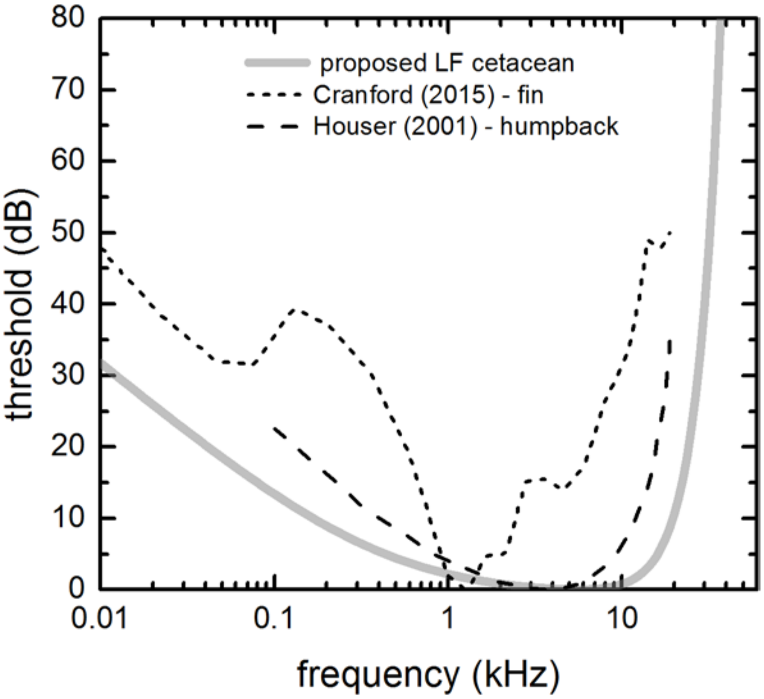

FIGURE A1.2. **Comparison of proposed LF cetacean thresholds to those predicted by anatomical and finite-element models.**

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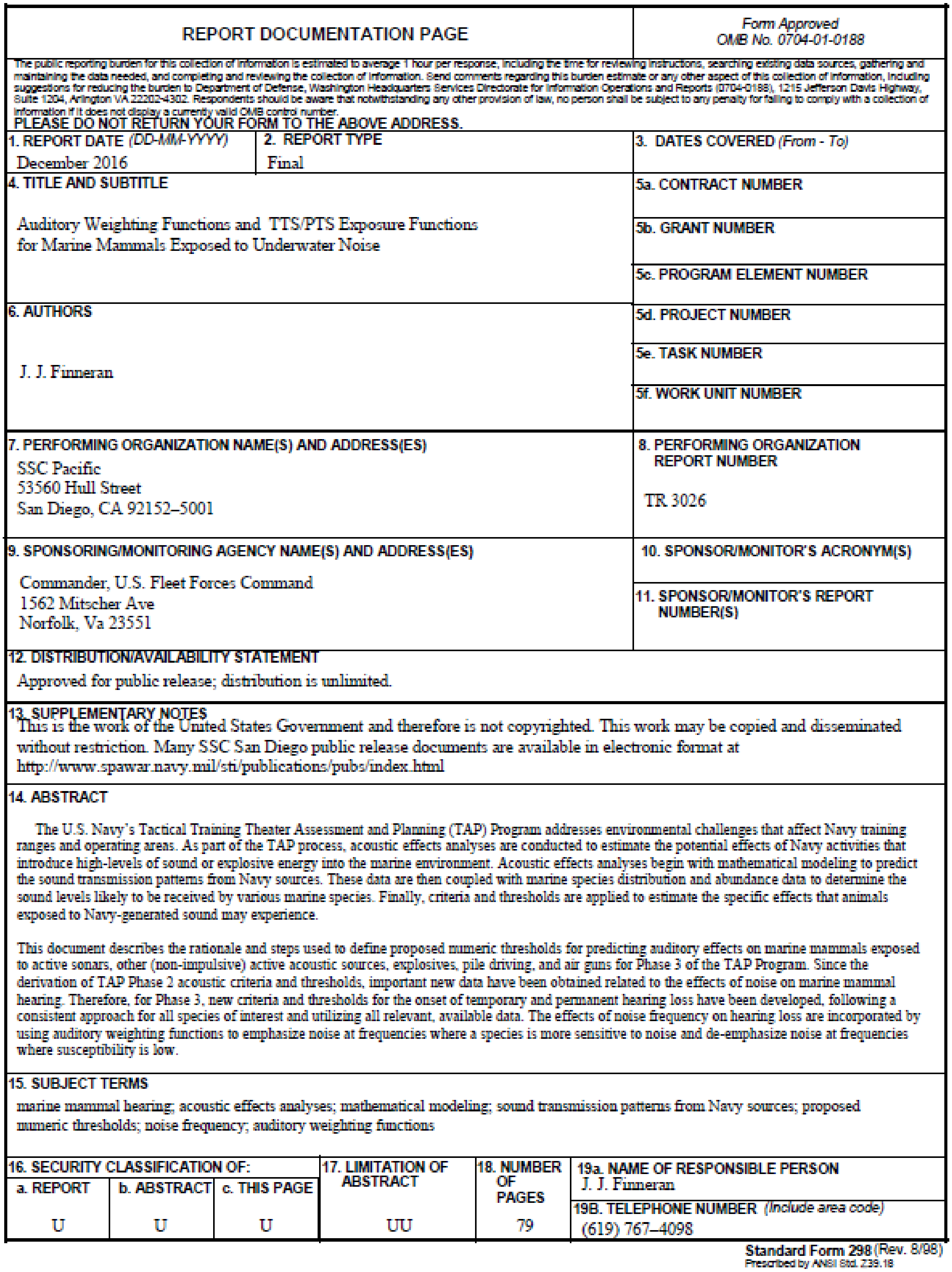

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14. ABSTRACT

The U.S. Navy's Tactical Training Theater Assessment and Planning (TAP) Program addresses environmental challenges that affect Navy training ranges and operating areas. As part of the TAP process, acoustic effects analyses are conducted to estimate the potential effects of Navy activities that introduce high-levels of sound or explosive energy into the marine environment. Acoustic effects analyses begin with mathematical modeling to predict the sound transmission patterns from Navy sources. These data are then coupled with marine species distribution and abundance data to determine the sound levels likely to be received by various marine species. Finally, criteria and thresholds are applied to estimate the specific effects that animals exposed to Navy-generated sound may experience.

This document describes the rationale and steps used to define proposed numeric thresholds for predicting auditory effects on marine mammals exposed to active sonars, other (non-impulsive) active acoustic sources, explosives, pile driving, and air guns for Phase 3 of the TAP Program. Since the derivation of TAP Phase 2 acoustic criteria and thresholds, important new data have been obtained related to the effects of noise on marine mammal hearing. Therefore, for Phase 3, new criteria and thresholds for the onset of temporary and permanent hearing loss have been developed, following a consistent approach for all species of interest and utilizing all relevant, available data. The effects of noise frequency on hearing loss are incorporated by using auditory weighting functions to emphasize noise at frequencies where a species is more sensitive to noise and de-emphasize noise at frequencies where susceptibility is low.

15. SUBJECT TERMS

marine mammal hearing; acoustic effects analyses; mathematical modeling; sound transmission patterns from Navy sources; proposed numeric thresholds; noise frequency; auditory weighting functions

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APPENDIX B: RESEARCH RECOMMENDATIONS FOR IMPROVED THRESHOLDS

In compiling, interpreting, and synthesizing the scientific literature to produce thresholds for this Technical Guidance, it is evident that additional data would be useful for future iterations of this document, since many data gaps still exist (Table B1). The need for the Technical Guidance to identify critical data gaps was also recommended during the initial peer review and public comment period.

Table B1: Summary of currently available marine mammal data.

Hearing Group	Audiogram Data/Number of Species	TTS Data/Number of Species	Sound Sources for TTS Studies
LF Cetaceans	Predictive modeling/2 species	None/0 species	None
MF Cetaceans	Behavioral/8 species	Behavioral/2 species	Octave-band noise; Tones; Mid-frequency sonar; Explosion simulator; Watergun; Airgun
HF Cetaceans	Behavioral/2 species	Behavioral/1 species	Tones, Mid-frequency sonar; Impact pile driver; Airgun*
PW Pinnipeds	Behavioral/5 species	Behavioral/2 species	Octave-band noise; Impact pile driver
OW Pinnipeds	Behavioral/3 species	Behavioral/1 species	Octave-band noise; Arc-gap transducer

* Data collected using AEP methodology (directly incorporated in Technical Guidance, since only data set available).

Below is a list of research recommendations that NMFS believes would help address current data gaps. Some of these areas of recommended research have been previously identified in other publications/reports (e.g., NRC 1994; NRC 2000; Southall et al. 2007; Southall et al. 2009; Hawkins et al. 2014;[38] Houser and Moore 2014; Lucke et al. 2014; Popper et al. 2014;[39] Williams et al. 2014; Erbe et al. 2016; Lucke et al. 2016). Note: Just because there may not be enough information to allow for quantifiable modifications to thresholds associated with many of these recommendations, does not mean these recommendations cannot be incorporated as qualitative considerations within the comprehensive effects analysis.

I. SUMMARY OF RESEARCH RECOMMENDATIONS

1.1 LOW-FREQUENCY CETACEAN HEARING

As previously stated, direct measurements of LF cetacean hearing are lacking. Therefore, hearing predictions for these species are based on other methods (e.g., anatomical studies, predictive models, vocalizations, taxonomy, and behavioral responses to sound). Thus, additional

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[38] Although, Hawkins et al. 2014 identifies research gaps for fishes and invertebrates, many of the research recommendations can also be considered for other species, like marine mammals.

[39] Although, Popper et al. 2014 identifies research gaps for fishes and sea turtles, many of the research recommendations can also be considered for other species, like marine mammals.

data[40] collected would be extremely valuable to furthering the understanding of hearing ability within this hearing group and validating other methods for approximating hearing ability. For example, data collected on either stranded or animals associated with subsistence hunts would be extremely useful in confirming current predictions of LF cetacean hearing ability and would allow for the development of more accurate auditory weighting functions (e.g., Do species that vocalize at ultra-low frequencies, like blue and fin whales, have dramatically different hearing abilities than other mysticete species?). Until direct measurements can be made, predictive models based on anatomical data will be the primary means of approximating hearing abilities, with validation remaining a critical component of any modeling exercise (e.g., Cranford and Krysl 2014).

1.2 HEARING DIVERSITY AMONG SPECIES AND AUDITORY PATHWAYS

A better understanding of hearing diversity among species within a hearing group is also needed (e.g., Mooney et al. 2014) to comprehend how representative certain species (e.g., bottlenose dolphins, harbor porpoise, harbor seals) are of their hearing group as a whole. For example, are there certain species more susceptible to hearing loss from sound (i.e., all members of HF cetaceans), or are there additional delineations needed among the current hearing groups (e.g., deep diving species, etc.)? Having more data from species within a hearing group would also help identify if additional hearing groups are needed. This is especially the case for HF cetaceans where data are only available from four individuals of two species and those individuals have a lower hearing threshold compared to all other hearing groups.

Additionally, having a more complete understanding of how sound enters the heads/bodies of marine mammals and its implication on hearing and impacts of noise among various species is another area of importance (e.g., bone conduction mechanism in mysticetes: Cranford and Krysl 2015; previously undescribed acoustic pathways in odontocetes: Cranford et al. 2008; Cranford et al. 2010; filtering/amplification of transmission pathway: Cranford and Krysl 2012; directional hearing: Renaud and Popper 1975; Au and Moore 1984; Kastelein et al. 2005b).

1.3 REPRESENTATIVENESS OF CAPTIVE INDIVIDUALS

Data from Castellote et al. (2014), from free-ranging belugas in Alaska, indicate that of the seven healthy individuals tested (3 females/4 males; 1 subadult/6 adults), all had hearing abilities “similar to those of belugas measured in zoological settings.” Similarly, data from Ruser et al. (2017) reported that harbor porpoise live-stranded (15 individuals both males and females; subadults and adults) and wild individuals incidentally caught in pound nets (12 both males and females; subadult and adults) had “the shape of the hearing curve is generally similar to previously published results from behavioral trials.” Thus, from these studies, it appears that for baseline hearing measurements, captive individuals may be appropriate surrogates for free-ranging animals. Additionally, Mulsow et al. (2011) measured aerial hearing abilities of seven stranded California sea lions and found a high degree of intersubject variability but that high-frequency hearing limits were consistent with previously tested captive individuals. However, these are currently the only studies of their kind,[41] and more research is needed to examine if this trend is applicable to other species (Lucke et al. 2016).

1.3.1 Impacts of Age on Hearing

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[40] Data should be collected under appropriate permits or authorizations.

[41] NMFS is aware that additional baseline hearing measurements have been recorded for additional free-ranging belugas by Castellote et al. with the analysis still in process. Furthermore, NMFS is aware that audiogram (AEP) data are often obtained during marine mammal stranding events exists, but these have yet to be published.

Hearing loss can result from a variety of factors beyond anthropogenic noise, including exposure to ototoxic compounds (chemicals poisonous to auditory structures), disease and infection, and heredity, as well as a natural part of aging (Corso 1959; Kearns 1977; WGSUA 1988; Yost 2007). High-frequency hearing loss, presumably a normal process of aging that occurs in humans and other terrestrial mammals, has also been demonstrated in captive cetaceans (Ridgway and Carder 1997; Yuen et al. 2005; Finneran et al. 2005b; Houser and Finneran 2006; Finneran et al. 2007b; Schlundt et al. 2011) and in stranded individuals (Mann et al. 2010). Thus, the potential impacts of age on hearing can be a concern when extrapolating from older to younger individuals.

Few studies have examined this phenomenon in marine mammals, particularly in terms of the potential impact of aging on hearing ability and TSs:

- Houser and Finneran (2006) conducted a comprehensive study of the hearing sensitivity of the U.S. Navy bottlenose dolphin population (i.e., tested 42 individuals from age four to 47 years; 28 males/14 females). They found that high-frequency hearing loss typically began between the ages of 20 and 30 years. However, the frequencies where this species is most susceptible to noise-induced hearing loss (i.e., 10 to 30 kHz) are the frequencies where the lowest variability exists in mean thresholds between individuals of different ages.

- Houser et al. (2008) measured hearing abilities of 13 Pacific bottlenose dolphins, ranging in age from 1.5 to 18 years. The authors' reported that "Variability in the range of hearing and age-related reductions in hearing sensitivity and range of hearing were consistent with those observed in Atlantic bottlenose dolphins."

- Mulsow et al. (2014) examined aerial hearing thresholds for 16 captive sea lions, from age one to 26 years, and found that only the two 26-year old individuals had hearing classified as "aberrant" compared to other individuals (i.e., high-frequency hearing loss), which were deemed to have similar hearing abilities to previously measured individuals.

- Additionally, for harbor seals, similar exposure levels associated with TTS onset were found in Kastelein et al. 2012a for individuals of four to five years of age compared to that used in Kastak et al. 2005, which was 14 years old and for belugas in Popov et al. 2014 for an individual of 2 years of age compared to those used in Schlundt et al. 2000, which were 20 to 22 years old or 29 to 31 years old.

From these limited data, it appears that age may not be a significant complicating factor, in terms of assessing TSs for animals of different ages. Nevertheless, additional data are needed to confirm if these data are representative for all species (Lucke et al. 2016).

1.4 ADDITIONAL TTS MEASUREMENTS WITH MORE SPECIES AND/OR INDIVIDUALS

Currently, TTS measurements only exist for four species of cetaceans (bottlenose dolphins, belugas, harbor porpoises, and Yangtze finless porpoise) and three species of pinnipeds (Northern elephant seal, harbor seal, and California sea lion). Additionally, the existing marine mammal TTS measurements are from a limited number of individuals within these species. Having more data from a broader range of species and individuals would be useful to confirm how representative current individuals are of their species and/or entire hearing groups (Lucke et al. 2016). For example, TTS onset thresholds for harbor porpoise (HF cetacean) are much lower compared to other odontocetes (MF cetaceans), and it would be useful to know if all HF cetaceans share these lower TTS onset thresholds or if harbor porpoises are the exception.

Measured underwater hearing of two captive spotted seals (Sills et al. 2014) and two captive ringed seals (Sills et al. 2015) found these species' hearing abilities are comparable to harbor seals. Thus, harbor seals, where TTS data are available, are an appropriate surrogate for ice seal species. As more data become available, this assumption will be re-evaluated.

Finally, cetaceans are often used as surrogates for pinnipeds when no direct data exist. Having more information on the appropriateness of using cetaceans as surrogates for pinnipeds would be useful (i.e., Is there another mammalian group more appropriate?).

1.5 SOUND EXPOSURE TO MORE REALISTIC SCENARIOS

Most marine mammal TTS measurements are for individuals exposed to a limited number of sound sources (i.e., mostly tones and octave-band noise[42]) in laboratory settings. Measurements from exposure to actual sound sources (opposed to tones or octave-band noise) under more realistic exposure conditions (e.g., more realistic exposure durations and/or scenarios, including multiple pulses/pile strikes and at frequencies below 1 kHz where most anthropogenic noise occurs) are needed.

1.5.1 Frequency and Duration of Exposure

In addition to received level, NMFS recognizes that other factors, such as frequency and duration of exposure, are also important to consider within the context of PTS onset thresholds (Table B2). However, there are not enough data to establish numerical thresholds based on these added factors (beyond what has already been included in this document, in terms of marine mammal auditory weighting functions and $\mathrm{SEL}_{\mathrm{cum}}$ thresholds). When more data become available, it may be possible to incorporate these factors into quantitative assessments.

Further, it has been demonstrated that exposure to lower-frequency broadband sounds has the potential to cause TSs at higher frequencies (e.g., Lucke et al. 2009; Kastelein et al. 2015a; Kastelein et al. 2016). The consideration of duty cycle (i.e., energy per unit time) is another important consideration in the context of exposure duration (e.g., Kastelein et al. 2015b). Having a better understanding of these phenomena would be helpful.

1.5.2 Multiple Sources

Further, a better understanding of the effects of multiple sources and multiple activities on TS, as well as impacts from long-term exposure is needed. Studies on terrestrial mammals indicate that exposure scenarios from complex exposures (i.e., those involving multiple types of sound sources) result in more complicated patterns of NIHL (e.g., Ahroon et al. 1993).

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[42] More recent studies (e.g., Lucke et al. 2009; Mooney et al. 2009b; Kastelein et al. 2014a; Kastelein et al. 2014b; Kastelein et al. 2015a; Kastelein et al. 2015b; Finneran et al. 2015; Kastelein et al. 2016; Kastelein et al. 2017b; Kastelein et al. 2017c) have used exposures from more realistic sources, like airguns, impact pile drivers, or tactical sonar.

Table B2: Additional factors for consideration (frequency and duration of exposure) in association with PTS onset thresholds.

I. Frequency*: <u>General Trend Identified</u>: 1) Growth of TS: Growth rates of TS (dB of TTS/dB noise) are higher for frequencies where hearing is more sensitive (e.g., Finneran and Schlundt 2010; Finneran and Schlundt 2013; Kastelein et al. 2014a; Kastelein et al. 2015b)
II. Duration: <u>General Trends Identified</u>: 1) Violation of EEH: Non-impulsive, intermittent exposures require higher SEL_{cum} to induce a TS compared to continuous exposures of the same duration (e.g., Mooney et al. 2009a; Finneran et al. 2010b; Kastelein et al. 2014a) 2) Violation of EEH: Exposures of longer duration and lower levels induce a TTS at a lower level than those exposures of higher level (below the critical level) and shorter duration with the same SEL_{cum} (e.g., Kastak et al. 2005; Kastak et al. 2007; Mooney et al. 2009b; Finneran et al. 2010a; Kastelein et al. 2012a; Kastelein et al. 2012b) 3) Recovery from a TS: With the same SEL_{cum}, longer exposures require longer durations to recover (e.g., Mooney et al. 2009b; Finneran et al. 2010a) 4) Recovery from a TS: Intermittent exposures recover faster compared to continuous exposures of the same duration (e.g., Finneran et al. 2010b; Kastelein et al. 2014a; Kastelein et al. 2015b)
III. Cumulative Exposure: <u>General Trend Identified:</u> 1) Animals may be exposed to multiple sound sources and stressors, beyond acoustics, during an activity, with the possibility of the possibility of additive or synergistic effects (e.g., Sih et al. 2004; Rohr et al. 2006; Chen et al. 2007; Lucke et al. 2016; NRC 2016)

* Frequency-dependent hearing loss and overall hearing ability within a hearing group is taken into account, quantitatively, with auditory weighting functions.

1.5.3 Possible Protective Mechanisms

Nachtigall and Supin (2013) reported that a false killer whale was able to reduce its hearing sensitivity (i.e., conditioned dampening of hearing) when a loud sound was preceded by a warning signal. Nachtigall and Supin (2014) reported a similar finding in a bottlenose dolphin, a beluga (Nachtigall et al. 2016a), and in harbor porpoises (Nacthigall et al. 2016b). Further studies showed that conditioning is associated with the frequency of the warning signal (Nachtigall and Supin 2015), as well as if an animal is able to anticipate when a loud sound is expected to occur after a warning signal (Nachtigall et al. 2016c).

Additionally, Finneran et al. (2015) observed two of the three dolphins in their study displayed “anticipatory” behavior (e.g., head movement) during an exposure sequence to multiple airgun shots. It is unknown if this behavior resulted in some mitigating effects of the exposure. Popov et al. (2016) investigated the impact of prolonged sound stimuli (i.e., 1500 s continuous pip successions vs. 500-msec pip trains) on the beluga auditory system and found that auditory adaptation occurred during exposure (i.e., decrease in amplitude of rate following response associated with evoked potentials) at levels below which TTS onset would likely be induced. The amount of amplitude reduction depended on stimulus duration, with higher reductions occurring during prolonged stimulation. The authors also caution that adaptation will vary with sound parameters. Finneran (2018) confirmed that bottlenose dolphins can "self mitigate" when warned of an upcoming exposure and that mechanism for this mitigation occurs in the cochlea or auditory nerve.

In the wild, potential protective mechanisms have been observed, with synchronous surfacing associated with exposure to playbacks of tactical sonar recorded in long-finned pilot whales (Miller et al. 2012). However, it is unclear how effective this behavior is in reducing received levels (Wensveen et al. 2015).

Thus, marine mammals may have multiple means of reducing or ameliorating the effects noise exposure. However, at this point, directly incorporating them into a comprehensive effects analysis that anticipates the likelihood of exposure ahead of an activity is difficult. More information on these mechanisms, especially associated with real-world exposure scenarios, would be useful.

1.5.4 Long-Term Consequences of Exposure

Kujawa and Liberman (2009) found that with large, but recoverable noise-induced thresholds shifts (maximum 40 dB TS measured by auditory brainstem response (ABR)), sound could cause delayed cochlear nerve degeneration in mice. Further, Lin et al. (2011) reported a similar pattern of neural degeneration in mice after large but recoverable noise-induced TSs (maximum ~50 dB TS measured by ABR), which suggests a common phenomenon in all mammals. The long-term consequences of this degeneration remain unclear.

Another study reported impaired auditory cortex function (i.e., behavioral and neural discrimination of sound in the temporal domain (discriminate between pulse trains of various repetition rates)) after sound exposure in rats that displayed no impairment in hearing (Zhou and Merzenich 2012). Zheng (2012) found reorganization of the neural networks in the primary auditory cortex (i.e., tonotopic map) of adult rats exposed to low-level noise, which suggests an adaptation to living in a noisy environment (e.g., noise exposed rats performed tasks better in noisy environment compared to control rats). Heeringa and van Dijk (2014) reported firing rates in the inferior colliculus of guinea pigs had a different recovery pattern compared to ABR thresholds. Thus, it is recommended that there be additional studies to look at these potential effects in marine mammals (Tougaard et al. 2015).

Finally, it is also important to understand how repeated exposures resulting in TTS could potentially lead to PTS (e.g., Kastak et al. 2008; Reichmuth 2009). For example, occupational noise standards, such as those from the Occupational Safety & Health Administration (OSHA), consider the impact of noise exposure over a lifetime of exposure (e.g., 29 CFR Part 1926 over 40 years). Similar, longer-term considerations are needed for marine mammals.

1.6 IMPACTS OF NOISE-INDUCED THRESHOLD SHIFTS ON FITNESS

When considering noise-induced thresholds shifts, it is important to understand that hearing is more than merely the mechanical process of the ear and neural coding of sound (detection). It also involves higher processing and integration with other stimuli (perception) (Yost 2007; Alain and Berstein 2008). Currently, more is known about the aspects of neural coding of sounds compared to the higher-level processing that occurs on an individual level.

Typically, effects of noise exposure resulting in energetic (Williams et al. 2006; Barber et al. 2010) and fitness consequences (increased mortality or decreased reproductive success) are deemed to have the potential to affect a population/stock (NRC 2005; Southall et al. 2007; SMRU Marine 2014) or as put by Gill et al. 2001 "From a conservation perspective, human disturbance of wildlife is important only if it affects survival or fecundity and hence causes a population to decline." The number of individuals exposed and the location and duration of exposure are important factors, as well. To determine whether a TS will result in a fitness consequence requires one to consider several factors.

First, one has to consider the likelihood an individual would be exposed for a long enough duration or to a high enough level to induce a TS (e.g., realistic exposure scenarios). Richardson et al. (1995) hypothesized that "Disturbance effects are likely to cause most marine mammals to avoid any 'zone of discomfort or nonauditory effects' that may exist" and that "The greatest risk of immediate hearing damage might be if a powerful source were turned on suddenly at full power while a mammal was nearby." It is uncertain how frequently individuals in the wild are experiencing situations where TSs are likely from individual sources (Richardson et al.1995; Erbe and Farmer 2000; Erbe 2002; Holt 2008; Mooney et al. 2009b).

In determining the severity of a TS, it is important to consider the magnitude of the TS, time to recovery (seconds to minutes or hours to days), the frequency range of the exposure, the frequency range of hearing and vocalization for the particular species (i.e., how animal uses sound in the frequency range of anthropogenic noise exposure; e.g., Kastelein et al. 2014b), and their overlap (e.g., spatial, temporal, and spectral). Richardson et al. (1995) noted, "To evaluate the importance of this temporary impairment, it would be necessary to consider the ways in which marine mammals use sound, and the consequences if access to this information were impaired." Thus, exposure to an anthropogenic sound source, may affect individuals and species differently (Sutherland 1996).

Finally, different degrees of hearing loss exist: ranging from slight/mild to moderate and from severe to profound (Clark 1981), with profound loss being synonymous with deafness (CDC 2004; WHO 2015). For hearing loss in humans, Miller (1974) summarized "any injury to the ear or any change in hearing threshold level that places it outside the normal range constitutes a hearing impairment. Whether a particular impairment constitutes a hearing handicap or a hearing disability can only be judged in relation to an individual's life pattern or occupation." This statement can translate to considering effects of hearing loss in marine mammals, as well (i.e., substituting "occupation" for "fitness").

Simply because a hearing impairment may be possible does not necessarily mean an individual will experience a disability in terms of overall fitness consequence. However, there needs to be a better understanding of the impacts of repeated exposures. As Kight and Swaddle (2011) indicate "Perhaps the most important unanswered question in anthropogenic noise research – and in anthropogenic disturbance research, in general – is how repeated exposure over a lifetime cumulatively impacts an individual, both over the short- (e.g. condition, survival) and long- (e.g., reproductive success) term." Thus, more research is needed to understand the true consequences of noise-induced TSs (acute and chronic) to overall fitness.

1.7 BEHAVIOR OF MARINE MAMMALS UNDER EXPOSURE CONDITIONS WITH THE POTENTIAL TO CAUSE HEARING IMPACTS

Although assessing the behavioral response of marine mammals to sound is outside the scope of this document, understanding these reactions, especially in terms of exposure conditions having the potential to cause NIHL is critical to be able to predict exposure better. Understanding marine mammal responses to anthropogenic sound exposure presents a set of unique challenges, which arise from the inherent complexity of behavioral reactions. Responses can depend on numerous factors, including intrinsic, natural extrinsic (e.g., ice cover, prey distribution), or anthropogenic, as well as the interplay among factors (Archer et al. 2010). Behavioral reactions can vary not only among individuals but also within an individual, depending on previous experience with a sound source, hearing sensitivity, sex, age, reproductive status, geographic location, season, health, social behavior, or context.

Severity of behavioral responses can also vary depending on characteristics associated with the sound source (e.g., whether it is moving or stationary, number of sound sources, distance from the source) or the potential for the source and individuals to co-occur temporally and spatially (e.g., persistence or recurrence of the sound in specific areas; how close to shore, region where animals may be unable to avoid exposure, propagation characteristics that are either enhancing or reducing exposure) (Richardson et al. 1995; NRC 2003; Wartzok et al. 2004; NRC 2005; Southall et al. 2007; Bejder et al. 2009).

Further, not all species or individuals react identically to anthropogenic sound exposure. There may be certain species-specific behaviors (e.g., fight or flight responses; particularly behaviorally sensitive species) that make a species or individuals of that species more or less likely to react to anthropogenic sound. Having this information would be useful in improving the recommended accumulations period (i.e., 24 h) and understanding situations where individuals are more likely to be exposed to noise over longer durations and are more at risk for NIHL, either temporary or permanent.

1.8 CHARACTERISTICS OF SOUND ASSOCIATED WITH NIHL AND IMPACTS OF PROPAGATION

It is known as sound propagates through the environment various physical characteristics change (e.g., frequency content with lower frequencies typically propagating further than higher frequencies; pulse length due to reverberation or multipath propagation in shallow and deep water). Having a better understanding of the characteristics of a sound that makes it injurious (e.g., peak pressure amplitude, rise time, pulse duration, etc.; Henderson and Hamernik 1986; NIOSH 1998) and how those characteristics change under various propagation conditions would be extremely helpful in the application of appropriate thresholds and be useful in supporting a better understanding as to how sounds could possess less injurious characteristics further from the source (e.g., transition range).

Further, validation and/or comparison of various propagation and exposure models for a variety of sources would be useful to regulators, who with thresholds that are more complex will be faced with evaluating the results from a multitude of models. This would also allow for a more complete comparison to the methodologies provided in this Technical Guidance. This would allow for a determination of how precautionary these methodologies are under various scenarios and allow for potential refinement.

1.9 NOISE-INDUCED THRESHOLD SHIFT GROWTH RATES AND RECOVERY

TS growth rate data for marine mammals are limited, with higher growth rates for frequencies where hearing is more sensitive (Finneran and Schlundt 2010; Finneran and Schlundt 2013; Kastelein et al. 2015b). Understanding how these trends vary with exposure to more complex sound sources (e.g., broadband impulsive sources) and among various species would be valuable.

Understanding recovery after sound exposure is also an important consideration. Currently, there is a lack of recovery data for marine mammals, especially for exposure to durations and levels expected under real-world scenarios. Thus, additional marine mammal noise-induced recovery data would be useful. A better understanding of likely exposure scenarios, including the potential for recovery, including how long after noise exposure recovery is likely to occur, could also improve the recommended baseline accumulation period.

1.10 METRICS AND TERMINOLOGY

Sound can be described using a variety of metrics, with some being more appropriate for certain sound types or effects compared with others (e.g., Coles et al. 1968; Hamernik et al. 2003; Madsen 2005; Davis et al. 2009; Zhu et al. 2009). A better understanding of the most appropriate metrics for establishing thresholds and predicting impacts to hearing would be useful in confirming the value of providing dual metric thresholds using the PK and weighted SEL_{cum} metrics for impulsive sources. As science advances, additional or more appropriate metrics may be identified and further incorporated by NMFS. However, caution is recommended when comparing sound descriptions in different metrics (i.e., they are not directly comparable). Additionally, the practicality of measuring and applying metrics is another important consideration.

Further, the Technical Guidance's thresholds are based on the EEH, which is known to be inaccurate in some situations. Popov et al. 2014 suggested that RMS SPL multiplied by log duration better described their data than the EEH. Thus, better means of describing the interaction between SPL and duration of exposure would be valuable.

Finally, in trying to define metrics and certain terms (e.g., impulsive and non-impulsive) within the context of the Technical Guidance, NMFS often found difficulties due to lack of universally accepted standards and common terminology. Within the Technical Guidance, NMFS has tried to adopt terminology, definitions, symbols, and abbreviations that reflect those of the American National Standards Institute (ANSI) or more appropriately the more recent International Organization for Standardization (ISO)[43]. Thus, NMFS encourages the further development of appropriate standards for marine application.

1.11 EFFECTIVE QUIET

"Effective quiet" is defined as the maximum sound pressure level that will fail to produce any significant TS in hearing despite duration of exposure and amount of accumulation (Ward et al. 1976; Ward 1991). Effective quiet can essentially be thought of as a "safe exposure level" (i.e., risks for TS are extremely low or nonexistent) in terms of hearing loss[44] (Mills 1982; NRC 1993) and is frequency dependent (Ward et al. 1976; Mills 1982). Effective quiet is an important consideration for the onset TTS and PTS thresholds expressed by the weighted SEL_{cum} metric because if not taken into consideration unrealistically low levels of exposure with long enough exposure durations could accumulate to exceed current weighted SEL_{cum} thresholds, when the likelihood of an actual TS is extremely low (e.g., humans exposed to continuous levels of normal speech levels throughout the day are not typically subjected to TTS from this type of exposure).

Currently, defining effective quiet for marine mammals is not possible due to lack of data. However, a study by Popov et al. 2014 on belugas exposed to half-octave noise centered at 22.5 kHz indicates that effective quiet for this exposure scenario and species might be around 154 dB. In Finneran's (2015) review of NIHL in marine mammals, effective quiet is predicted to vary by species (e.g., below 150 to 160 dB for bottlenose dolphins and belugas; below 140 dB for Yangtze finless porpoise; 124 dB for harbor porpoise; and 174 dB for California sea lions).

As more data become available, they would be useful in contributing to the better understanding of appropriate accumulations periods for the weighted SEL_{cum} metric and NIHL, as well as the potential of low-level (e.g., Coping et al. 2014; Schuster et al. 2015), continuously operating sources (e.g., alternative energy tidal, wave, or wind turbines) to induce noise-induced hearing loss.

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[43] This version (2.0) of Technical Guidance is more reflective of ISO 18405 (ISO 2017). ISO 18405 is the preferred standard because it was developed specifically for underwater acoustics, compared with standards developed for airborne acoustics that use different conventions.

[44] <u>Note</u>: "Effective quiet" only applies to hearing loss and not to behavioral response (i.e., levels below "effective quiet" could result in behavioral responses). It also is separate consideration from defining "quiet" areas (NMFS 2009).

1.12 TRANSLATING BIOLOGICAL COMPLEXITY INTO PRACTICAL APPLICATION

Although, not a specific research recommendation, practical application of science is an important consideration. As more is learned about the potential effects of sound on marine mammals, the more complex future thresholds are likely to become. For example, before the 2016 Technical Guidance, NMFS primarily relied on two generic thresholds for assessing auditory impacts, with one for cetaceans (SPL RMS 180 dB) and one for pinnipeds (SPL RMS 190 dB). In this document, these two simple thresholds have now been replaced by ten PTS onset thresholds (with dual metrics for impulsive sounds), including the addition of auditory weighting functions. Although, these thresholds better represent the current state of knowledge, they have created additional challenges for implementation. Practical application always needs to be weighed against making thresholds overly complicated (cost vs. benefit considerations). The creation of tools to help ensure action proponents, as well as managers apply complex thresholds correctly, is a critical need.

Additionally, there is always a need for basic, practical acoustic training opportunities for action proponents and managers (most acoustic classes available are for students within an academic setting and not necessarily those who deal with acoustics in a more applied manner). Having the background tools and knowledge to be able to implement the Technical Guidance is critical to this document being a useful and effective tool in assessing the effects of noise on marine mammal hearing.

APPENDIX C: TECHNICAL GUIDANCE REVIEW PROCESSES: PEER REVIEW, PUBLIC COMMENT, AND REVIEW UNDER EXECUTIVE ORDER 13795

The Technical Guidance (NMFS 2016a) before its finalization in 2016 went through several stages of peer review and public comment. Additionally, this document underwent further review under E0 13795.

I. PEER REVIEW PROCESS

The President's Office Management and Budget (OMB 2005) states, "Peer review is one of the important procedures used to ensure that the quality of published information meets the standards of the scientific and technical community. It is a form of deliberation involving an exchange of judgments about the appropriateness of methods and the strength of the author's inferences. Peer review involves the review of a draft product for quality by specialists in the field who were not involved in producing the draft."

The peer review of this document was conducted in accordance with NOAA's Information Quality Guidelines[45] (IQG), which were designed for "ensuring and maximizing the quality, objectivity, utility, and integrity of information disseminated by the agency" (with each of these terms defined within the IQG). Further, the IQG stipulate that "To the degree that the agency action is based on science, NOAA will use (a) the best available science and supporting studies (including peer-reviewed science and supporting studies when available), conducted in accordance with sound and objective scientific practices, and (b) data collected by accepted methods or best available methods." Under the IQG and in consistent with OMB's Final Information Quality Bulletin for Peer Review (OMB Peer Review Bulletin (OMB 2005), the Technical Guidance was considered a Highly Influential Scientific Assessments (HISA),[46] and peer review was required before it could be disseminated by the Federal Government. OMB (2005) notes "Peer review should not be confused with public comment and other stakeholder processes. The selection of participants in a peer review is based on expertise, with due consideration of independence and conflict of interest."

The peer review of the Technical Guidance (NMFS 2016a) consisted of three independent reviews covering various aspects of the document: 1) There was an initial peer review of the entire draft Guidance in 2013, 2) a second peer review in March/April 2015 that focused on newly available science from the Finneran Technical Report (Finneran 2016; See Appendix A), and 3) a third peer review in April 2015 in response to public comments received during the initial public comment period, which focused on a particular technical section relating to the proposed application of impulsive and non-impulsive PTS onset thresholds based on physical characteristics at the source and how those characteristics change with range.[47] Upon completion of the three peer reviews, NMFS was required to post and respond to all peer reviewer comments received via three separate Peer Review Reports.

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[45] NOAA's Information Quality Guidelines.

[46] "Its dissemination could have a potential impact of more than $500 million in any one year on either the public or private sector; or that the dissemination is novel, controversial, or precedent-setting; or that it has significant interagency interest" (OMB 2005). The Technical Guidance is not a regulatory action subject to a cost-benefit analysis under Executive Orders12866 and 13563. The Technical Guidance was classified as a HISA because it was novel and precedent setting, not due to the potential financial implications.

[47] Note: Upon evaluation of public comment received during the Technical Guidance's second public comment period (July 2015), NMFS decided to postpone implementing this methodology until more data were available to support its use.

1.1 2013 INITIAL PEER REVIEW (ASSOCIATED WITH 2013 DRAFT GUIDANCE)

For the initial peer review of this document (July to September 2013), potential qualified peer reviewers were nominated by a steering committee put together by the MMC. The steering committee consisted of MMC Commissioners and members of the Committee of Scientific Advisors (Dr. Daryl Boness, Dr. Douglas Wartzok, and Dr. Sue Moore).

Nominated peer reviewers were those with expertise marine mammalogy, acoustics/bioacoustics, and/or acoustics in the marine environment. Of the ten nominated reviewers, four volunteered, had no conflicts of interest, had the appropriate area of expertise,[48] and were available to complete an individual review (Table C1). The focus of the peer review was on the scientific/technical studies that have been applied and the manner that they have been applied in this document.

Table C1: Initial peer review panel.

Name	Affiliation
Dr. Paul Nachtigall	University of Hawaii
Dr. Doug Nowacek	Duke University
Dr. Klaus Lucke*	Wageningen University and Research (The Netherlands)
Dr. Aaron Thode	Scripps Institution of Oceanography

* Present affiliation: Curtin University (Australia).

Peer reviewers' comments and NMFS' responses to the comments, from this initial peer review, can be found at: Link to Technical Guidance's Peer Review Plan.

1.2 2015 SECOND PEER REVIEW (REVIEW OF THE FINNERAN TECHNICAL REPORT)

For their Phase 3 Acoustic Effects Analysis, the U.S. Navy provided NMFS with a technical report, by Dr. James Finneran, describing their proposed methodology for updating auditory weighting functions and subsequent numeric thresholds for predicting auditory effects (TTS/PTS thresholds) on marine animals exposed to active sonars, other (non-impulsive) active acoustic sources, explosives, pile driving, and air guns utilized during Navy training and testing activities.

Upon evaluation, NMFS preliminarily determined that the proposed methodology, within the Finneran Technical Report (Finneran 2016), reflected the scientific literature and decided to incorporate it into the Technical Guidance. Before doing so, we commissioned an independent peer review of the Finneran Technical Report (i.e. second peer review). Note: Reviewers were not asked to review the entire Technical Guidance document.

For the second peer review (March to April 2015), NMFS again requested the assistance of the MMC to nominate peer reviewers. As with the initial peer review, potential qualified peer reviewers were nominated by a steering committee put together by the MMC, which consisted of MMC Commissioners and members of the Committee of Scientific Advisors (Dr. Daryl Boness, Dr. Douglas Wartzok, and Dr. Sue Moore).
Nominated peer reviewers were those with expertise[49] specifically in marine mammal hearing (i.e., behavior and/or AEP) and/or noise-induced hearing loss. Of the twelve nominated

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[48] Reviewer credentials are posted at: Link to Technical Guidance's Peer Review Plan.

[49] Reviewer credentials are posted at: Link to Technical Guidance's Peer Review Plan.

reviewers, four volunteered, had not conflicts of interest, had the appropriate area of expertise, and were available to complete an individual review of the Finneran Technical Report (Table C2).

Table C2: Second peer review panel.

Name	Affiliation
Dr. Whitlow Au	University of Hawaii
Dr. Colleen Le Prell	University of Florida*
Dr. Klaus Lucke	Curtin University (Australia)
Dr. Jack Terhune	University of New Brunswick (Canada)

*Affiliation during initial review (Affiliation during follow-up peer review: The University of Texas at Dallas.

Peer reviewers' comments and NMFS' responses to the comments, from the second peer review, can be found at: Link to Technical Guidance's Peer Review Plan.

1.2.1 2016 Follow-Up to Second Peer Review

Concurrent with the Technical Guidance's third public comment period (see Section 2.3 of this appendix), a follow-up peer review was conducted. The focus of this peer review was whether the 2016 Proposed Changes to the Technical Guidance, associated with the third public comment period, would substantially change any of the peer reviewers' comments provided during their original review (i.e., peer reviewers were not asked to re-review the Finneran Technical Report). Additionally, peer reviewers were not asked to comment on any potential policy or legal implications of the application of the Technical Guidance, or on the amount of uncertainty that is acceptable or the amount of precaution that should be embedded in any regulatory analysis of impacts.

All four previous peer reviewers were available to perform the follow-up peer review. Peer reviewers' comments and NMFS' responses to the comments, from this follow-up peer review, can be found at: Link to Technical Guidance's Peer Review Plan.

1.3 2015 THIRD PEER REVIEW (REVIEW OF TRANSITION RANGE METHODOLOGY)

During the Technical Guidance's initial public comment period, NMFS received numerous comments relating to how the Technical Guidance classifies acoustic sources based on characteristics at the source (i.e., non-impulsive vs. impulsive). Many expressed concern that as sound propagates through the environment and eventually reaches a receiver (i.e., marine mammal) that physical characteristics of the sound may change and that NMFS' categorization may not be fully reflective of real-world scenarios. Thus, NMFS re-evaluated its methodology for categorizing sound sources to reflect these concerns. Thus, a third peer review focused on particular technical section relating to the Technical Guidance's proposed application of impulsive and non-impulsive PTS onset thresholds based on physical characteristics at the source and how those characteristics change with range (i.e., transition range). Note: Reviewers were not asked to review the entire Technical Guidance document.

Since the focus of the third peer review was focused on the physical changes a sound experiences as it propagates through the environment, the Acoustical Society of America's Underwater Technical Council was asked to nominate peer reviewers with expertise in underwater sound propagation and physical characteristics of impulsive sources, especially high explosives, seismic airguns, and/or impact pile drivers. Of the six nominated reviewers, two volunteered, were available, had no conflicts of interest, and had the appropriate area of expertise[50] to complete an individual review of the technical section (Table C3).

Additionally, NMFS wanted peer reviewers with expertise in marine and terrestrial mammal noise-induced hearing loss to review this technical section and ensure the proposed methodology was ground-truthed in current biological knowledge. Thus, NMFS re-evaluated peer reviewer nominees previously made by the MMC for the first and second peer reviews. From this list, two reviewers volunteered, were available, had no conflicts of interest, and had the appropriate area of expertise to serve as peer reviewers (Table C3).

Table C3: Third peer review panel.

Name	Affiliation
Dr. Robert Burkard	University at Buffalo
Dr. Peter Dahl*	University of Washington
Dr. Colleen Reichmuth+	University of California Santa Cruz
Dr. Kevin Williams*	University of Washington

* Peer reviewers with expertise in underwater acoustic propagation.

\+ Dr. Reichmuth was an alternate on the MMC original peer reviewer nomination list.

Peer reviewers' comments and NMFS' responses to the comments, from the third peer review, can be found at: Link to Technical Guidance's Peer Review Plan.

Note: In response to public comments made during the second public comment period, NMFS decided to withdraw its proposed transition range methodology until more data can be collected to better support this concept (i.e., see Appendix B: Research Recommendations).

1.4 CONFLICT OF INTEREST DISCLOSURE

Each peer reviewer (i.e., initial, second, and third peer review) completed a conflict of interest disclosure form. It is essential that peer reviewers of NMFS influential scientific information (ISI) or HISA not be compromised by any significant conflict of interest. For this purpose, the term "conflict of interest" means any financial or other interest which conflicts with the service of the individual because it (1) could significantly impair the individual's objectivity or (2) could create an unfair competitive advantage for any person or organization. No individual can be appointed to review information subject to the OMB Peer Review Bulletin if the individual has a conflict of interest that is relevant to the functions to be performed.

The following website contains information on the peer review process including: the charge to peer reviewers, peer reviewers' names, peer reviewers' individual reports, and NMFS' response to peer reviewer reports.

II. PUBLIC COMMENT PERIODS

In addition to the peer review process, NMFS recognizes the importance of feedback from action proponents/stakeholders and other members of the public. The focus of the public comment process was on both the technical aspects of the document, as well as the implementation of the science in NMFS' policy decisions under the various applicable statutes. The first two public

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[50] Reviewer Credentials.

comment periods were held after the peer review to ensure the public received the most scientifically sound product for review and comment. A third public focused comment period was held after incorporation of recommendations made by NMFS and Navy scientists (SSC-PAC) during further evaluation of the Finneran Technical Report after the second public comment period. During this third public comment period, there was a concurrent follow-up peer review. See section 1.2.1 above.

2.1 2013/2014 INITIAL PUBLIC COMMENT PERIOD (ASSOCIATED WITH 2013 DRAFT TECHNICAL GUIDANCE)

A public meeting/webinar was held to inform interested parties and solicit comments on the first publicly available version of the Draft Technical Guidance. The meeting/webinar was held on January 14, 2014, in the NOAA Science Center in Silver Spring, Maryland. The presentation and transcript from this meeting is available electronically.

This public comment period was advertised via the Federal Register and originally lasted 30 days, opening on December 27, 2013 (NMFS 2013). During this 30-day period, multiple groups requested that the public comment period be extended beyond 30 days. Thus, the public comment period was extended an additional 45 days and closed on March 13, 2014 (NMFS 2014).

2.1.1 Summary of Public Comments Received

A total of 129[51] comments were received from individuals, groups, organizations, and affiliations. Twenty-eight of these were in the form of a letter, spreadsheet, or individual comment submitted by representatives of a group/organization/affiliation (some submitted on behalf of an organization and/or as an individual). Those commenting included: 11 members of Congress; eight state/federal/international government agencies; two Alaskan native groups; seven industry groups; five individual subject matter experts; a scientific professional organization; 12 non-governmental organizations; an environmental consulting firm; and a regulatory watchdog group. Each provided substantive comments addressing technical aspects or issues relating to the implementation of thresholds, which were addressed in the Final Technical Guidance or related Federal Register Notice.[52]

Of those not mentioned above, an additional 101 comments were submitted in the form of a letter or individual comment. Twelve of these comments specifically requested an extension of the original 30-day public comment period (a 45-day extension to original public comment period was granted). The remaining 89 comments were not directly applicable to the Technical Guidance (e.g., general concern over impacts of noise on marine mammals from various industry or military activities) and were not further addressed. Specific comments can be viewed on Regulations.gov.

NMFS' responses to substantive comments made during the initial public comment period were published in the Federal Register located on the following web site in conjunction with the Final Technical Guidance.

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[51] Of this number, one comment was directed to the Federal Communications Commission (i.e., not meant for the Technical Guidance) and one commenter submitted their comments twice. In addition, one comment was not included in this total, nor posted because it contained threatening language.

[52] With the updates made to the Technical Guidance as a result of the second and third peer reviews, some of the comments made during the initial public comment period were no longer relevant and as such were not addressed.

2.2 2015 SECOND PUBLIC COMMENT PERIOD (ASSOCIATED WITH 2015 DRAFT TECHNICAL GUIDANCE)

Because of the significant changes made to the Draft Technical Guidance from the two additional peer reviews, NMFS proposed a second 45-day public comment, which occurred in the summer of 2015. Notice of this public comment period was published in the Federal Register on July 31, 2015, and closed September 14, 2015 (NMFS 2015).

2.2.1 Summary of Public Comments Received

A total of 20 comments were received from individuals, groups, organizations, and affiliations in the form of a letter or individual comment submitted by representatives of a group/organization/affiliation (some submitted on behalf of an organization and/or as an individual). Those commenting included: two federal agencies; four industry groups; seven subject matter experts; a scientific professional organization; seven non-governmental organizations; two Alaskan native groups; an environmental consulting firm; and a regulatory watchdog group. Each provided substantive comments addressing technical aspects and/or issues relating to the implementation of thresholds, which were addressed in the Final Technical Guidance or related Federal Register Notice.

Of those not mentioned above, an additional four comments were submitted in the form of a letter or individual comment. One of these comments specifically requested an extension of the 45-day public comment period, while the remaining three comments were not directly applicable to the Technical Guidance (e.g., general concern over impacts of noise on marine mammals from various industry or military activities) and were not further addressed. Specific comments can be viewed on Regulations.gov.

NMFS responses to substantive comments made during the second public comment period were published in the Federal Register located on the following web site in conjunction with the Final Technical Guidance: Link to Technical Guidance web page.

2.3 2016 THIRD PUBLIC COMMENT PERIOD (ASSOCIATED WITH 2016 PROPOSED CHANGES FROM DRAFT TECHNICAL GUIDANCE)[53]

While NMFS was working to address public comments and finalize the Technical Guidance, after the second public comment period, the Finneran Technical Report was further evaluated internally by NMFS, as well as externally by Navy scientists (SSC-PAC). As a result, several recommendations/modifications were suggested.

The recommendations included:

- Modification of methodology to establish predicted the composite audiogram and weighting/exposure functions for LF cetaceans

- Modification of the methodology used to establish thresholds for LF cetaceans

- Movement of the white-beaked dolphin (*Lagenorhynchus albirostris*) from MF to HF cetaceans[54]

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[53] Concurrent with this third public comment period, NMFS requested that the peer reviewers of the Finneran Technical Report review the Draft Technical Guidance's proposed changes and indicate if the revisions would significantly alter any of the comments made during their original review (i.e., follow-up to second peer review).

[54] Upon re-evaluation and considering comments made during the third public comment period, it was decided this move was not fully supported (i.e., move not supported to the level of that of the other two species in this family). Thus, this species remains a MF cetacean.

- Inclusion of a newly published harbor porpoise audiogram (HF cetacean) from Kastelein et al. 2015c

- The exclusion of multiple data sets, based on expert evaluation, from the phocid pinniped auditory weighting function

- Removal of PK thresholds for non-impulsive sounds

- Use of dynamic range to predict PK thresholds for hearing groups where impulsive data did not exist.

After consideration of these recommendations, NMFS proposed to update the Draft Technical Guidance to reflect these suggested changes and solicited public comment on the revised sections of the document via a focused 14-day public comment period. This public comment period was advertised via the Federal Register and opened on March 16, 2016, and closed March 30, 2016 (NMFS 2016b).

2.3.1 Summary of Public Comments Received

A total of 20[55] comments were received from individuals, groups, organizations, and affiliations in the form of a letter or individual comment submitted by representatives of a group/organization/affiliation (some submitted on behalf of an organization and/or as an individual). Those commenting included: two federal agencies; seven industry groups; three subject matter experts; a scientific professional organization; and nine non-governmental organizations. Each provided substantive comments addressing technical aspects and/or issues relating to the implementation of thresholds, which were addressed in the Final Technical Guidance or related Federal Register Notice.

Of those not mentioned above, an additional comment was submitted from a member of the public in the form of an individual comment. Three of these comments specifically requested an extension[56] of the 14-day public comment period. Specific comments can be viewed on Regulations.gov.

NMFS responses to substantive comments made during the third public comment period were published in the Federal Register located on the following web site in conjunction with the Final Technical Guidance.

2.4 CHANGES TO TECHNICAL GUIDANCE AS A RESULT OF PUBLIC COMMENTS

Public comment provided NMFS with valuable input during the development of the Technical Guidance. As a result of public comments, numerous changes were incorporated in the Final Technical Guidance, with the most significant being:

- Re-examination and consideration of LF auditory weighting function and thresholds throughout the public comment process

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[55] One group of commenters had trouble in submitting their public comments via regulations.gov. As a result, their duplicate comments were submitted three times and were counted toward this total of 20 public comments.

[56] The majority of the 20 comments received requested an extension of the public comment period. Three comments were from industry groups that only requested an extension and never provided additional comments (i.e., others in additional to requesting an extension provided substantive comments).

- Updated methodology (dynamic range) for approximating PK thresholds for species where TTS data from impulsive sources were not available

- Removal of PK thresholds for non-impulsive sources

- Addition of an appendix providing research recommendations

- Adoption of a consistent accumulation period (24-h)

- More consistent means of defining generalized hearing range for each marine mammal hearing group based on ~65 dB threshold from the normalized composite audiogram.

- Modification to reflect ANSI standard symbols and abbreviations.

- Withdraw of the proposed transition range methodology (July 2015 Draft) until more data can be collected to better support this concept. Instead, this concept has been moved to Research Recommendations (Appendix B).

- Replacement of alternative thresholds with weighting factor adjustments (WFAs) that more accurately allow those incapable of fully implementing the auditory weighting functions to implement this concept (Technical Guidance; Appendix D).

III. REVIEW UNDER EXECUTIVE ORDER 13795

Presidential Executive Order (EO) 13795, Implementing an America-First Offshore Energy Strategy (82 FR 20815; April 28, 2017), stated in section 2 that “It shall be the policy of the United States to encourage energy exploration and production, including on the Outer Continental Shelf, in order to maintain the Nation’s position as a global energy leader and foster energy security and resilience for the benefit of the American people, while ensuring that any such activity is safe and environmentally responsible.” Section 10 of the EO called for a review of the 2016 Technical Guidance for Assessing the Effects of Anthropogenic Sound on Marine Mammal Hearing (Technical Guidance; NMFS 2016a) as follows: “The Secretary of Commerce shall review [Technical Guidance] for consistency with the policy set forth in Section 2 of this order and, after consultation with the appropriate Federal agencies, take all steps permitted by law to rescind or revise that guidance, if appropriate.”

3.1 REVIEW OF 2016 TECHNICAL GUIDANCE UNDER EO 13795

3.1.1 2017 Public Comment Period

To assist the Secretary in carrying out that directive under EO 13795, NMFS held a 45-day public comment period (82 FR 24950; May 31, 2017) to solicit comments on the Technical Guidance (NMFS 2016a) for consistency with the EO’s policy.

3.1.1.1 Summary of Comments Received

NMFS received 62 comments directly related to the 2016 Technical Guidance.[57] Comments were submitted by Federal agencies (Bureau of Ocean Energy Management (BOEM), U.S. Navy,

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[57] NMFS received an additional 137 comments during the Technical Guidance’s public comment period relating to an overlapping public comment period for “Takes of Marine Mammals Incidental to Specified Activities; Taking Marine Mammals Incidental to Geophysical Surveys in the Atlantic Ocean” (82 FR 26244). Thus, the majority (approximately 70%) of public comments NMFS received during the Technical Guidance’s public comment period related to the proposed action of oil and gas activity in the Atlantic.

MMC), oil and gas industry representatives, Members of Congress, subject matter experts, non-governmental organizations, a foreign statutory advisory group, a regulatory advocacy group, and members of the public (Table C4).

Table C4: Summary of commenters

Commenter Category	Specific Commenter
U.S. Federal agencies	Bureau of Ocean Energy Management; Marine Mammal Commission; U.S. Navy
Members of Congress*	22 members
Oil & gas industry representatives	American Petroleum Institute/International Association of Geophysical Contractors/Alaska Oil and Gas Association/National Ocean Industries Association
Non-Governmental Organization	Natural Resources Defense Council/The Human Society of the US/Whale and Dolphin Conservation; Ocean Conservation Research
Regulatory advocacy group	Center for Regulatory Effectiveness
Foreign statutory advisor Group	Joint Nature Conservation Committee
Subject matter experts (SME)	Marine scientist/mammologist; Geophysicist/Geochemist; Acoustician
General public	47 members

; indicates separate comments, while / indicates comments submitted together.

* Letter sent directly to Secretary Ross (i.e., not submitted to Regulations.gov).

Most of the comments (85%) recommended no changes to the Technical Guidance, and no public commenter suggested rescinding the Technical Guidance. The U.S. Navy, Marine Mammal Commission, Members of Congress, and subject matter experts expressed support for the Technical Guidance's thresholds and weighting functions as reflecting the best available science. The remaining comments (15%) focused on additional scientific publications for consideration or recommended revisions to improve implementation of the Technical Guidance. All public comments received during this review can be found at: Regulations.gov.

3.1.2 2017 Federal Interagency Consultation

Further, to assist the Secretary in carrying out the directive under EO 13795, NMFS invited, via letter, 15 Federal agencies to participate in an in-person meeting (i.e., Interagency Consultation) on September 25, 2017, at NMFS Headquarters in Silver Spring, Maryland, to serve as a formal forum to discuss this document and provide additional comments. Ten of the eleven[58] expected Federal agencies participated in this meeting (Table C5).

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[58] The U.S Fish & Wildlife Service, U.S. Coast Guard, and The U.S. Environmental Protection Agency declined NMFS' invitation to participate. U.S. Department of Energy did not reply.

Table C5: Ten Federal agency attendees*

Bureau of Ocean Energy Management	National Science Foundation
Department of State	U.S. Air Force
Federal Highway Administration	U.S. Army Corps of Engineers
Marine Mammal Commission	U.S. Geological Survey+
National Park Service	U.S. Navy

*Bureau of Safety and Environmental Enforcement did not attend.

+USGS participated via webinar/teleconference.

3.1.2.1 Summary of Interagency Comments

At the Federal Interagency Consultation, none of the Federal agencies recommended rescinding the Technical Guidance. Federal agencies were supportive of the Technical Guidance's thresholds and auditory weighting functions and the science behind their derivation and were appreciative of the opportunity to provide input. Comments received at the meeting focused on improvements to implementation of the Technical Guidance and recommendations for future working group discussions to address implementation of the Technical Guidance based on any new scientific information as it becomes available.

3.2 REVISIONS TO THE 2016 TECHNICAL GUIDANCE AS A RESULT OF REVIEW UNDER EO 13795

NMFS acknowledges the importance of supporting sustainable ocean use, such as energy exploration and production on the Outer Continental Shelf, provided activities are conducted in a safe and environmentally responsible manner. Our development and implementation of the Technical Guidance are consistent with allowing activities vital to our nation's security and economy to proceed, including those mentioned in EO 13795, and allows for decisions to be made based upon the best available information.

The EO 13795 review process provided NMFS the opportunity to acquire valuable feedback from the public/stakeholders and Federal agencies on the 2016 Technical Guidance and its implementation, since its finalization. During both NMFS' public comment period and Federal Interagency Consultation, neither the public/stakeholders nor Federal agencies recommended the 2016 Technical Guidance (NMFS 2016a) be rescinded. Most comments were supportive of the thresholds and auditory weighting functions within 2016 Technical Guidance. Of those providing comments, most offered recommendations for improving the clarity of the document and facilitating implementation.

During both the public comment period and the Federal Interagency Consultation, three key topic areas were raised: (1) the limited scientific data on the impacts of sound on LF cetacean hearing; (2) the need to determine the accumulation period for all species of marine mammals; and (3) the need to improve the 2016 Technical Guidance's optional User Spreadsheet tool. Commenters also encouraged the agency to establish working groups to address these data gaps and future needs.

NMFS' evaluation of comments received during this process affirms that the Technical Guidance is based on the best available science. Nevertheless, based on consideration of comments received and per the approval of the Secretary of Commerce, NMFS made the following revisions to the 2016 Technical Guidance and/or companion User Spreadsheet tool to improve implementation and facilitate its use by action proponents, thereby further advancing the policy in section 2 of EO. 13795 (as reflected in this 2018 Technical Guidance, Version 2.0):

- To promote a more realistic assessment of the potential impacts of sound on marine mammal hearing, using the Technical Guidance, NMFS will re-evaluate implementation of the default 24-h accumulation period and plans to convene a working group later in 2018 to investigate means for deriving more realistic accumulation periods.

- To understand further the impacts of sound on hearing of LF cetaceans, a marine mammal group where no direct data on hearing exists, NMFS plans to convene a working group later in 2018 to explore this topic. NMFS will incorporate any changes that may result from the working group's efforts in future updates to the Technical Guidance.

- NMFS created a new User Manual for NMFS' User Spreadsheet tool that provides detailed instructions and examples on how to use this optional tool. This new User Manual (NMFS 2018) is available at: Link to Technical Guidance web page. NMFS plans to submit the User Manual for public comment later in 2018 to gain input from stakeholders and inform future versions of the User Manual.

- NMFS issued an updated optional User Spreadsheet tool to provide PTS onset isopleths associated with the Technical Guidance's PK thresholds associated with impulsive sources, so action proponents will not have to perform this calculation separately. The modified version (Version 2.0) of the optional User Spreadsheet tool is available at: Link to Technical Guidance web page.

- NMFS issued an updated optional User Spreadsheet tool to include a custom sheet for vibratory pile driving activities to facilitate the ease of assessing PTS onset for this commonly used sound source. Custom tabs for multiple and single explosives/detonations were also added to the updated optional User Spreadsheet tool. These custom tabs, within the optional User Spreadsheet tool (Version 2.0), are available at: Link to Technical Guidance web page.

- NMFS summarized and conducted a preliminary analysis of the relevant scientific literature published since the 2016 Technical Guidance's finalization (Section 3.1.1).

- NMFS modified the Technical Guidance threshold's symbols and glossary to be more reflective of the International Organization for Standardization (ISO) 2017 Underwater Acoustics – Terminology standard (ISO 18405), which was specifically developed for underwater acoustics.

- Appendix A has been updated to include the Navy's finalized version (Technical Report 3026, December 2016) of their Technical Report that NMFS used to derive the Technical Guidance's thresholds and auditory weighting functions.

- To increase understanding of how regulatory programs use and recommend the use of the Technical Guidance, which would facilitate implementation and thereby further advance the Policy in section 2 of EO 13795, NMFS is developing a separate document describing how the Technical Guidance is used in the MMPA incidental take authorization process to estimate "take" and inform mitigation decisions.. This document, once available, will be found at: Link to Incidental Take Authorization web page.

Note: Several comments received during both the public comment period and Federal Interagency Consultation were beyond the scope of the Technical Guidance and/or its review under section 10 of EO 13795. However, NMFS is evaluating these recommendations and determining the best way to address them via other means outside this review.

APPENDIX D: ALTERNATIVE METHODOLOGY

I. INTRODUCTION

This Appendix is provided to assist action proponents in the application of thresholds presented in this Technical Guidance. Since the adoption of NMFS' original thresholds for assessing auditory impacts (i.e., RMS SPL: 180 dB for cetaceans; 190 dB for pinnipeds), the understanding of the effects of noise on marine mammal hearing has greatly advanced (e.g., Southall et al. 2007; Finneran 2015; Finneran 2016) making it necessary to re-examine the current state of science and our thresholds. However, NMFS recognizes in updating our thresholds to reflect the scientific literature, they have become more complex.

This Appendix provides a set of alternative tools, examples, and weighting factor adjustments (WFAs) to allow action proponents with different levels of exposure modeling capabilities to be able to apply NMFS' thresholds for the onset of PTS for all sound sources. These tools are incorporated in NMFS' optional User Spreadsheet tool, with examples provided in the recently developed User Spreadsheet Manual (NMFS 2018)[59].

There is no obligation to use the optional User Spreadsheet tool, and the use of more sophisticated exposure modeling or consideration of additional action- or location-specific factors, if possible, is encouraged.

II. WEIGHTING FACTOR ADJUSTMENT ASSOCIATED WITH SEL_{CUM} THRESHOLDS

Numerical criteria presented in the Technical Guidance consist of both an acoustic threshold and auditory weighting function associated with the SEL_{cum} metric. NMFS recognizes that the implementation of marine mammal auditory weighting functions represents a new factor for consideration, which may extend beyond the capabilities of some action proponents. Thus, NMFS has developed simple weighting factor adjustments (WFA) for those who cannot fully apply auditory weighting functions associated with the SEL_{cum} metric.

WFAs consider marine mammal auditory weighting functions by focusing on a single frequency. This will typically result in similar, if not identical, predicted exposures for narrowband sounds or higher predicted exposures for broadband sounds, since only one frequency is being considered, compared to exposures associated with the ability to fully incorporate the Technical Guidance's auditory weighting functions.

WFAs use the same thresholds contained in the Technical Guidance and allow adjustments to be made for each hearing group based on source-specific information.

NMFS has provided a companion User Spreadsheet tool and User Manual for the User Spreadsheet tool to help action proponents incorporate WFAs to determine isopleths for PTS onset associated with their activity: Link to Technical Guidance web page.

2.1 APPLICATION FOR NARROWBAND SOUNDS

For narrowband sources, the selection of the appropriate frequency for consideration associated with WFAs is straightforward. WFAs for a narrowband sound would take the auditory weighting

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[59] The most recent version of the optional User Spreadsheet tool and companion User Manual (NMFS 2018) is available at: Link to Technical Guidance web page.

function amplitude, for each hearing group, associated with the particular frequency of interest and use it to make an adjustment to reflect the hearing's group susceptibility to that narrowband sound.

As an example, a 1 kHz narrowband sound would result in the following WFAs:

- LF cetaceans: -0.06 dB
- MF cetaceans: -29.11 dB
- HF cetaceans: -37.55 dB
- Phocid pinnipeds: -5.90 dB
- Otariid pinnipeds: -4.87 dB

As this example illustrates, WFAs always result in zero or a negative dB amplitude. Additionally, the more a sound's frequency is outside a hearing group's most susceptible range (most susceptible range is where the weighting function amplitude equal zero), the more negative WFA that results (i.e., in example above 1 kHz is outside the most susceptible range for MF and HF cetaceans but in the most susceptible range for LF cetaceans; Figure D1). Further, the more negative WFA that results will lead to a smaller effect distance (isopleth) compared to a less negative or zero WFA. In other words, considering an identical weighted SEL_{cum} acoustic threshold, a more negative WFA (i.e., source outside most susceptible frequency range) will result in a smaller effect distance (isopleth) compared to one that is less negative or closer to zero (i.e., source inside most susceptible frequency range; Figure D2).

Note: NMFS reminds action proponents to be aware and consider that sources may not always adhere to manufacturer specifications and only produce sound within the specified frequency (i.e., often sources are capable of producing sounds, like harmonics and subharmonics, outside their specified bands; Deng et al. 2014; Hastie et al. 2014). If it is unclear whether a source is narrowband or not, please consult with NMFS.

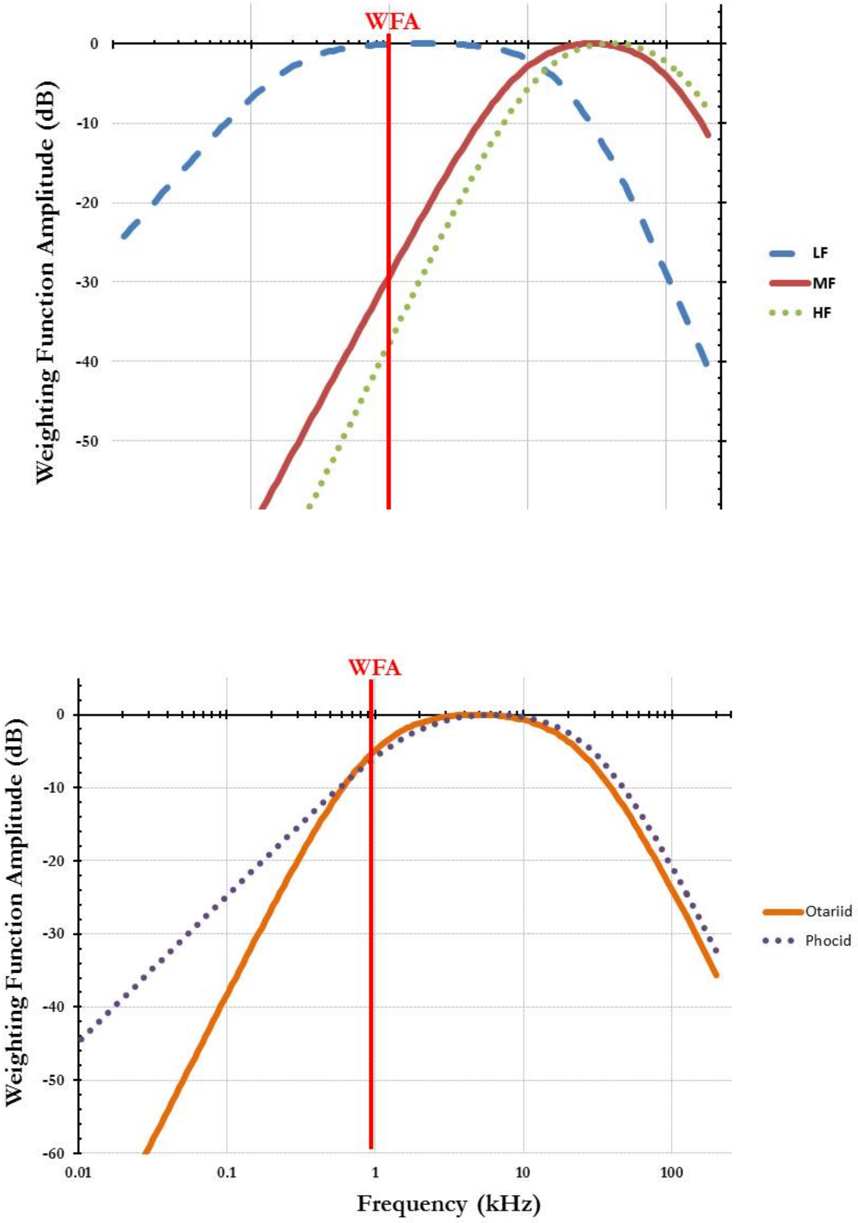

Figure D1: Example illustrating concept of weighting factor adjustment at 1 kHz (solid red line) with cetacean (top) and pinniped (bottom) auditory weighting functions.

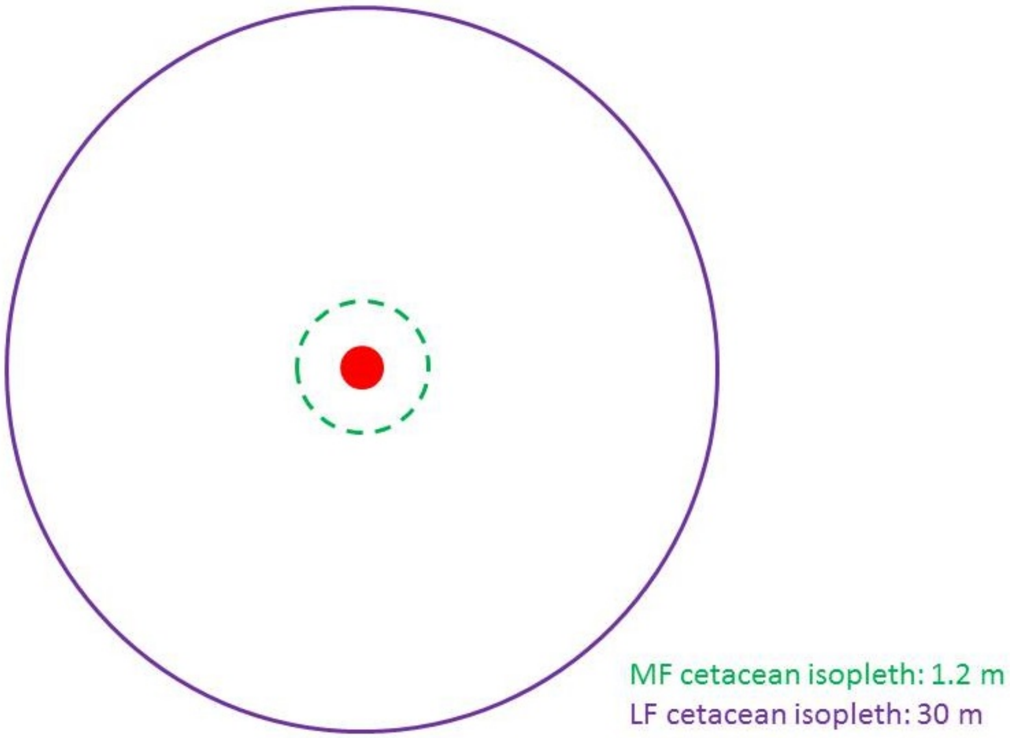

Figure D2: **Simple example illustrating concept of weighting factor adjustment on isopleths for LF and MF cetaceans using hypothetical 1 kHz narrowband, intermittent source represented by the red dot (RMS source level of 200 dB; 1-second ping every 2 minutes). For a non-impulsive source, the PTS onset weighted SEL_{cum} threshold for LF cetaceans is 199 dB, while for MF cetaceans is 198 dB. Despite LF cetaceans having a higher PTS onset threshold than MF cetaceans, the isopleth associated with LF cetaceans (30 m solid purple circle) is larger than that for MF cetaceans (1.2 m dashed green circle) based on 1 kHz being within LF cetacean's most susceptible frequency range vs. outside the most susceptible frequency range for MF cetaceans (isopleths not to scale).**

2.2 APPLICATION FOR BROADBAND SOUNDS

For broadband sources, the selection of the appropriate frequency for consideration associated with WFAs is more complicated. The selection of WFAs associated with broadband sources is similar to the concept used for to determine the 90% total cumulative energy window (5 to 95%) for consideration of duration associated with the RMS metric and impulsive sounds (Madsen 2005) but considered in the frequency domain, rather than the time domain. This is typically referred to as the 95% frequency contour percentile (Upper frequency below which 95% of total cumulative energy is contained; Charif et al. 2010).

NMFS recognizes the consideration of WFAs may be new for action proponents and have provided representative "default" values for various broadband sources (see associated User Spreadsheet tool and User Manual for User Spreadsheet tool).

2.2.1 Special Considerations for Broadband Source

Since the intent of WFAs is to broadly account for auditory weighting functions below the 95% frequency contour percentile, it is important that only frequencies on the "left side" of the auditory weighting function be used to make adjustments (i.e., frequencies below those where the auditory weighting function amplitude is zero[60] or below where the function is essentially flat; resulting in every frequency below the WFA always having a more negative amplitude than the chosen WFA) (Figure D3). It is inappropriate to use WFAs for frequencies on the "right side" of the auditory weighting function (i.e., frequencies above those where the auditory weighting function amplitude is zero). For a frequency on the "right side" of the auditory weighting function (Table D1), any adjustment is inappropriate and WFAs cannot be used (i.e., an action proponent would be advised to not use auditory weighting functions and evaluate its source as essentially unweighted; see "Use" frequencies in Table D1, which will result in a auditory weighting function amplitude of 0 dB).

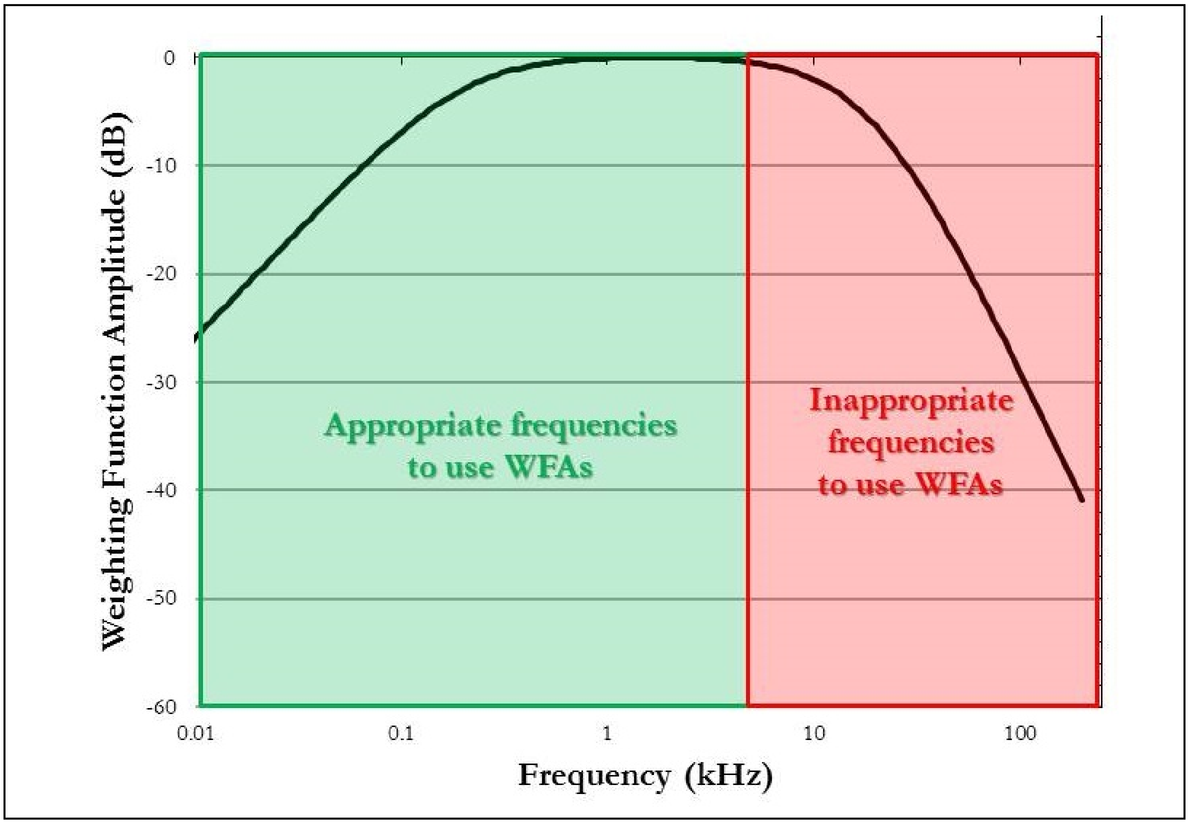

Figure D3: **Example auditory weighting function illustrating where the use of weighting factor adjustments are (Green: "left side") and are not (Red: "right side") appropriate for broadband sources.**

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[60] A criteria of a -0.4 dB weighting function amplitude from the Technical Guidance's auditory weighting function was used to determine the demarcation between appropriate and inappropriate frequencies to use the WFAs.

Table D1: Applicability of weighting factor adjustments for frequencies associated with broadband sounds

Hearing Group	Applicable Frequencies	Non-Applicable Frequencies*
Low-Frequency Cetaceans (LF)	4.8 kHz and lower	Above 4.8 kHz (Use: 1.7 kHz)
Mid-Frequency Cetaceans (MF)	43 kHz and lower	Above 43 kHz (Use: 28 kHz)
High-Frequency Cetaceans (HF)	59 kHz and lower	Above 59 kHz (Use: 42 kHz)
Phocid Pinnipeds (PW)	11 kHz and lower	Above 11 kHz (Use: 6.2 kHz)
Otariid Pinnipeds (OW)	8.5 kHz and lower	Above 8.5 kHz (Use: 4.9 kHz)

* With non-applicable frequencies, users input the "use" frequency in the User Spreadsheet tool, which will result in an auditory weighting function amplitude of 0 dB (i.e., unweighted).

2.3 OVERRIDING THE WEIGHTING FACTOR ADJUSTMENT

An action proponent is not obligated to use WFAs. If an action proponent has data or measurements depicting the spectrum of their sound source, they may use these data to override the User Spreadsheet WFA output. By including a source's entire spectrum, this will allow an action proponent to incorporate the Technical Guidance's marine mammal auditory weighting functions over the entire broadband frequency range of the source, rather than just for one frequency via the WFA. As a result, overriding the optional User Spreadsheet's WFA with a sound sources' spectrum will result in more realistic (i.e., likely smaller) isopleths. NMFS is currently evaluating whether surrogate spectrum are available and applicable for particular sound sources, if an applicant does not have data of their own to use.

As an example, Figure 118 in Appendix D of the Final Environmental Impact Statement for Gulf of Mexico OCS Proposed Geological and Geophysical Activities (BOEM 2017) provides a generic spectrum for an 8000 in^3 airgun array (Figure D4).

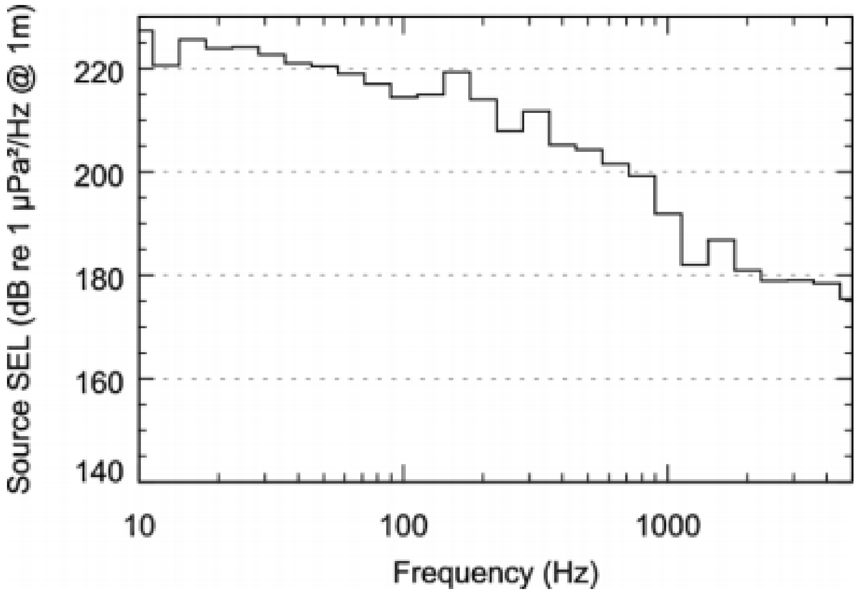

Figure D4: Maximum one-third octave band source level in the horizontal plane for a generic 8000 in^3 seismic array (BOEM 2017)

Table D2 provides a comparison of the dB adjustment between using the BOEM 2017 spectrum used to override the optional User Spreadsheet tool's default WFA and the direct use of the default WFA. As NMFS has stated previously, the more factors an action proponent can incorporate in their modeling, the more realistic results expected.

Table D2: Comparison of adjustment (dB) associated with incorporating entire broadband spectrum vs. default, single frequency WFA for a seismic array.

Weighting	LF cetacean	MF cetacean	HF cetacean	PW pinniped	OW pinniped
Default WFA (1 kHz)	-0.06 dB	-29.11 dB	-37.55 dB	-5.90 dB	-4.87 dB
Seismic array spectrum (BOEM 2017)*	-12.7 dB	-57.4 dB	-65.7 dB	-28.7 dB	-33.6 dB

* BOEM 2017 spectrum digitized using WebPlotDigitizer: Link to WebPlotDigitizer web page.

III. MODELING CUMULATIVE SOUND EXPOSURE LEVELS

To apply the PTS onset thresholds expressed as the weighted SEL_{cum} metric, a specified accumulation period is necessary. Generally, it is predicted that most receivers will minimize their time in the closest ranges to a sound source/activity and that exposures at the closest point of approach are the primary exposures contributing to a receiver's accumulated level (Gedamke et al. 2011). Additionally, several important factors determine the likelihood and duration of time a receiver is expected to be in close proximity to a sound source (i.e., overlap in space and time between the source and receiver). For example, accumulation time for fast moving (relative to the receiver), mobile source, is driven primarily by the characteristics of source (i.e., transit speed, duty cycle). Conversely, for stationary sources, accumulation time is driven primarily by the characteristics of the receiver (i.e., swim speed and whether species is transient or resident to the area where the activity is occurring). For all sources, NMFS recommends a baseline accumulation period of 24-h, but acknowledges that there may be specific exposure situations where this accumulation period requires an adjustment (e.g., if activity lasts less than 24 hours or for situations where receivers are predicted to experience unusually long exposure durations[61]).

Previous NMFS thresholds only accounted for the proximity of the sound source to the receiver, but thresholds in the Technical Guidance (i.e., expressed as weighted SEL_{cum}) now take into account the duration of exposure. NMFS recognizes that accounting for duration of exposure, although supported by the science literature, adds a new factor, as far as the application of this metric to real-world activities and that all action proponents may not have the ability to easily incorporate this additional component. NMFS does not provide specifications necessary to perform exposure modeling and relies on the action proponent to determine the model that best represents their activity.

3.1 MORE SOPHISTICATED MODELS

Because of the time component associated with the weighted $SEL_{cum\ metric}$, the use of different types of models to predict sound exposure may necessitate different approaches in evaluating likely effects in the context of the PTS onset thresholds. All marine mammals and some sources move in space and time, however, not all models are able to simulate relative source and receiver movement. Additionally, some models are able to predict the received level of sound at each modeled animal (often called animats) and accumulate sound at these receivers while incorporating the changing model environment.

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[61] For example, where a resident population could be found in a small and/or confined area (Ferguson et al. 2015) and/or exposed to a long-duration activity with a large sound source, or there could be a continuous stationery activity nearby an area where marine mammals congregate, like a pinniped pupping beach.

Models that are more sophisticated may allow for the inclusion of added details to achieve more realistic results based on the accumulation of sound (e.g. information on residence time of individuals, swim speeds for transient species, or specific times when activity temporarily ceases). Alternatively, there may be case-specific circumstances where the accumulation time needs to be modified to account for situations where animals are expected to be in closer proximity to the source over a significantly longer amount of time, based on activity, site, and species-specific information (e.g., where a resident population could be found in a small and/or confined area (Ferguson et al. 2015) and a long-duration activity with a large sound source, or a continuous stationery activity nearby a pinniped pupping beach).

3.2 LESS SOPHISTICATED MODELS

For action proponents unable to incorporate animal and/or source movement, it may not be realistic to assume that animals will remain at a constant distance from the source accumulating acoustic energy for 24 hours. Thus, alternative methods are needed, which can provide a distance from the source where exposure exceeding a threshold is expected to occur and can be used in the same manner as distance has been used to calculate exposures above previous NMFS thresholds. NMFS proposes two alternative methods: one for mobile sources and one for stationary sources.

3.2.1 Mobile Sources[62]

3.2.1.1 Linear Equivalents Used in Appendix

In underwater acoustics, equations/derivations are typically expressed in terms of logarithmic terms (i.e., levels). These equations can be further simplified by introducing linear equivalents of the levels (i.e., factors) related by multiplication instead of by addition. For example, source level[63] (SL) is replaced by the "source factor" $10^{\mathrm{SL}/(10\ \mathrm{dB})}$ (Ainslie 2010). In this appendix, the following linear equivalents are used:

- Sound exposure ($\mathcal{E}$) = $10^{\mathrm{SEL}/(10\ \mathrm{dB})}$ μPa²s
- Mean-square sound pressure ($\overline{p^2}$) = $10^{\mathrm{SPL}/(10\ \mathrm{dB})}$ μPa²
- Source factor ($\mathcal{S}$) = $10^{\mathrm{SL}/(10\ \mathrm{dB})}$ μPa²m²
- Energy source factor[64] ($\mathcal{S}_{\mathcal{E}}$) = $10^{\mathrm{SL}_E/(10\ \mathrm{dB})}$μPa² m²s

Both source level and energy source level (and their corresponding factors) are evaluated and reported in the direction producing the maximum SL.

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[62] The methodology for mobile sources presented in this Appendix underwent peer review via the publication process (Sivle et al. 2014) but did not undergo a separate peer review. It is an optional tool for the application of the thresholds presented in the Technical Guidance.

[63] For definition of SL, see Ainslie 2010. SL ≡ $10\log_{10}[p(s)^2 s^2/(1\ \mu\mathrm{Pa}^2\ \mathrm{m}^2)]$ dB (Ainslie writes this as SL ≡ $10\log_{10} p^2 s^2$ dB re 1 μPa²s m².) For a point source, s is a small distance from the source, where distortions due to absorption, refraction, reflection, or diffraction are negligible and $p(s)$ is the RMS sound pressure at that distance. For a large (i.e., finite) source, p is the hypothetical sound pressure that would exist at distance s from a point source with the same far-field radiant intensity as the true source. For further clarification, see ISO 2017, entry 3.3.2.1 "source level."

[64] For definition of SL_E, see Ainslie 2010. SL_E ≡ $10\log_{10}[E(s)s^2/(1\ \mu\mathrm{Pa}^2\ \mathrm{m}^2\ \mathrm{s})]$ dB (Ainslie writes this as SL_E ≡10 $\log_{10} E(s)s^2$ dB 1 μPa² m²s). For a point source, s is a small distance from the source, where distortions due to absorption, refraction, reflection, or diffraction are negligible and $E(s)$ is the unweighted sound exposure at that distance. For a large (i.e., finite) source, E is the hypothetical sound exposure that would exist at distance s from a point source with the same duration and far-field radiant intensity as the true source. For further clarification, see ISO 2017, entry 3.3.2.2 "energy source level."

3.2.1.2 “Safe Distance” Methodology

Cumulative sound exposure can be computed using a simple equation, assuming a constant received sound pressure level (SPL) that does not change over space and time[65] (Equation D1.; e.g., Urick 1983; ANSI 1986; Madsen 2005):

$$\mathrm{SEL_{cum}} = \mathrm{SPL} + 10 \log_{10} (\text{duration of exposure, expressed in seconds})\ \mathrm{dB}$$

Equation D1

However, if one assumes a stationary receiver and a source moving at a constant speed in a constant direction, then exposure changes over space and time (i.e., greatest rate of accumulation at closest point of approach).

An alternative approach for modeling moving sources is the concept of a “safe distance” (R_0), which is defined by Sivle et al. (2014) as “the distance from the source beyond which a threshold[66] for that metric ($\mathrm{SPL_0}$ or $\mathrm{SEL_0}$) is not exceeded.” This concept allows one to determine at what distance from a source a receiver would have to remain in order not to exceed a predetermined exposure threshold (i.e., E_0 which equals the weighted $\mathrm{SEL_{cum}}$ PTS onset threshold in this Technical Guidance) and is further illustrated in Figure D5.

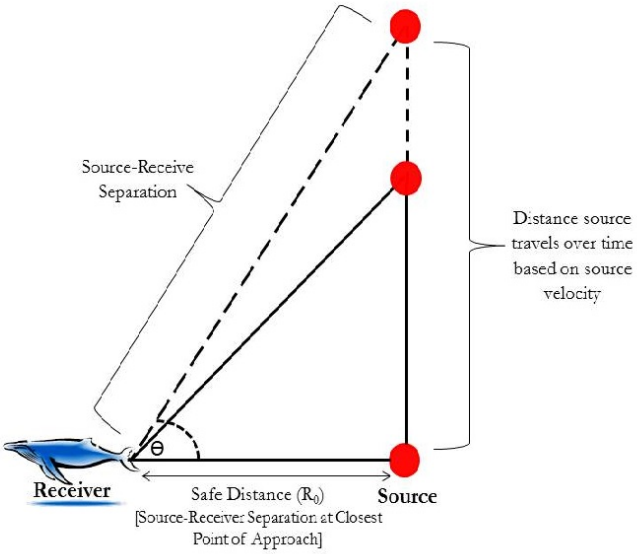

Figure D5: **Illustration of the concept for mobile sources, with each red dot representing the source traveling over time. As the source travels further from the receiver, the source-receiver separation increases (i.e., hypotenuse gets longer).**

This methodology accounts for several factors, including source level, duty cycle, and transit speed of the source and is independent of exposure duration (Equations D2a[67],b).

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[65] Equation D1 assumes a constant source-receiver separation distance.

[66] The threshold considered by Sivle et al. 2014 was associated with behavioral reactions.

[67] This equation matches Equation 3 from Sivle et al. (2014), but is written in a simpler manner.

a

$$R_0 = \frac{\pi}{E_0 v} SD$$

Equations D2a,b

For impulsive sources, SD is replaced with S_E/τ:

b

$$R_0 = \frac{\pi}{E_0 v} \frac{S_E}{\tau}$$

where:

S = source factor ($10^{\mathrm{SL}/(10\ \mathrm{dB})}$ µPa^{2}m^2)
D =duty cycle (pulse duration x repetition rate)
v= transit speed
E_0 =exposure threshold ($10^{\mathrm{SEL}_0/(10\ \mathrm{dB})}$ µPa^{2}s)
S_E = energy source factor ($10^{\mathrm{SL}_E/(10\ \mathrm{dB})}$µPa^{2}m^{2}s)
τ = 1/repetition rate

R_0 represents the exposure isopleth calculated using NMFS' thresholds. Thus, area calculations and exposure calculations would be performed in the same manner[68] action proponents have previously used (e.g., determine area covered over a 24-h period multiplied by the density of a marine mammal species).

This approach considers four factors:

1. Source level (direct relationship: as source level increases, so does R_0; higher source level results is a greater accumulation of energy).

2. Duty cycle (direct relationship: as duty cycle increases, so does R_0; higher duty cycle results in more energy within a unit of time and leads a greater accumulation of energy).

3. Source transit speed (inverse relationship: as transit speed decreases, R_0 increases or vice versa; a faster transit speed results in less energy within a unit of time and leads to a lower accumulation of energy, while a slower transit speed will result in a greater accumulation of energy).

4. Exposure threshold (inverse relationship: as the exposure threshold decreases, R_0 increases or vice versa; a higher exposure threshold result in needing more energy to exceed it compared to a lower threshold).

The action proponent is responsible for providing information on factors one through three above, while factor four is the PTS onset acoustic threshold (expressed as weighted $\mathrm{SEL}_{\mathrm{cum}}$ metric) provided within the Technical Guidance.

For this approach to be applicable to a broad range of activities, the following assumptions[69] are made:

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[68] Note: "Take" calculations are typically based on speed expressed in kilometers per hour, duration of an exposure expressed in hours (i.e., 24 hours), isopleths expressed in kilometers, and animal density expresses as animals per square kilometers. Thus, units would need to be converted to use Equations D2a,b.

[69] If any of these assumptions are violated and there is concern that the isopleth produced is potentially underestimated, it is recommended action proponents contact NMFS to see if any there are any appropriate adjustments that can be made (e.g., addition of a buffer, etc.). If not, the action proponent is advised to pursue other methodology capable of more accurately modeling exposure.

- Action proponents that are unable to apply full auditory weighting functions will rely on WFAs. This will create larger isopleths, for broadband sources, compared to action proponents capable of fully applying auditory weighting functions. Note: Action proponents can override the WFA if spectral data for their sound source is available (See Section 2.3 of this Appendix).

- The movement of the source is simple (i.e., source moves at a constant speed and in a constant direction). Caution is recommended if the source has the potential to move in a manner where the same group of receivers could be exposed to multiple passes from the source.

- Minimal assumptions are made about the receivers. They are considered stationary and assumed to not move up or down within the water column. There is no avoidance and the receiver accumulates sound via one pass of the source (i.e., receiver is not exposed to multiple passes from the source). Because this methodology only examines one pass of the source relative to receiver, this method is essentially time-independent (i.e., action proponent does not need to specify how long an activity occurs within a 24-h period).
    - These assumptions are appropriate for sources that are expected to move much faster than the receiver does. Further, assuming receivers do not avoid the source or change position vertically or horizontally in the water column will result in more exposures exceeding the thresholds compared to those receivers that would avoid or naturally change positions in the water column over time. Caution is recommended if the receiver has the potential to follow or move with the sound source.

- Distance (i.e., velocity x change over time) between “pulses” for intermittent sources is small compared with R_0, and the distance between “pulses” for intermittent sources is consistent. This assumption is appropriate for intermittent sources with a predictable duty cycle. If the duty cycle decreases, R_0 will become larger, while if the duty cycle increases, it will become smaller. Further, for intermittent sources, it is assumed there is no recovery in hearing threshold between pulses.

- Sound propagation is simple (i.e., approach uses spherical spreading[70]: 20 log R, with no absorption). NMFS recognizes that this might not be appropriate for all activities, especially those occurring in shallow water (i.e., sound could propagate further than predicted by this model)[71]. Thus, modifications to the R_0 predicted may be necessary in these situations.

Despite these assumptions, this approach offers a better approximation of the source-receiver distance over space and time for various mobile sources than choosing a set accumulation period for all sources, which assumes a fixed source-receiver distance over that time.

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[70] Assuming spherical spreading allows for Equations D2a,b to remain simplified (i.e., assuming another spreading model results in more complicated equations that are no longer user-friendly nor as easy to implement).

[71] Note: Many moving sources, like seismic airguns or sonar, can be highly-directional (i.e., most of time sound source is directed to the ocean floor, with less sound propagating horizontally, compared to the vertical direction), which is not accounted for with this methodology. Additionally, many higher-frequency sounds, like sonar, are also attenuated by absorption, which is also taken into account in this model. These, among other factors, are recommended for consideration when evaluating whether spherical spreading is potentially resulting in an underestimation of exposure.

Ainslie and Von Benda-Beckmann (2013) investigated the effect various factors had on the derivation of R_0 and found exposures were highest for stationary receivers in the path of a source, compared to mobile receivers swimming away from the source. However, the authors did acknowledge, if the receivers actively swam toward the source, cumulative exposure would increase. Uncertainty associated with R_0 was found to be primarily driven by the exposure threshold (i.e., Technical Guidance's thresholds). Increasing duty cycle of the source or reducing speed (either source or receiver) will result in an increased R_0 (Sivle et al. 2014)

NMFS has provided a companion User Spreadsheet tool and User Manual for the User Spreadsheet tool to help action proponents use this methodology to determine isopleths for PTS onset associated with their activity (Link to Technical Guidance web page).

3.2.2 Stationary Sources

If there is enough information to accurately predict the travel speed of a receiver past a stationary sound source (including the assumption that the receiver swims on a straight trajectory past the source), then the mobile source approach can be modified for stationary sources (i.e., transit speed of the source is replaced by speed of the receiver). However, NMFS acknowledges that characteristics of the receiver are less predictable compared to those of the source (i.e., velocity and travel path), which is why the mobile source approach may not be appropriate for stationary sources and an alternate method is provided below.

An alternative approach is to calculate the accumulated isopleth associated with a stationary sound source within a 24-h period. For example, if vibratory pile driving was expected to occur over ten hours within a 24-h period, then the isopleth would be calculated by adding area with each second the source is producing sound. This is a highly conservative means of calculating an isopleth because it assumes that animals on the edge of the isopleth (in order to exceed a threshold) will remain there for the entire time of the activity.

For stationary, impulsive sources with high source levels (i.e., impulsive pile driving associated with large piles, stationary airguns associated with vertical seismic profiling (VSPs), and large explosives) accumulating over a 24-h period, depending on how many strikes or shots occur, could lead to unrealistically large isopleths associated with PTS onset. For these situations, action proponents are advised to contact NMFS for possible applicable alternative methods.

NMFS has provided a companion User Spreadsheet tool and User Manual (NMFS 2018) for the User Spreadsheet tool to help action proponents wanting to use this methodology to determine isopleths for PTS onset associated with their activity (Link to Technical Guidance web page).

APPENDIX E: GLOSSARY

95% Frequency contour percentile: Upper frequency below which 95% of total cumulative energy is contained (Charif et al. 2010).

Accumulation period: The amount of time a sound accumulates for the SEL_{cum} metric.

Acoustic threshold: An acoustic threshold in this document identifies the level of sound, after which exceeded, NMFS anticipates a change in auditory sensitivity (temporary or permanent threshold shift).

Ambient noise: All-encompassing sound at a given place, usually a composite of sound from many sources near and far (ANSI 1994).

Animat: A simulated marine mammal.

Anthropogenic: Originating (caused or produced by) from human activity.

Audible: Heard or capable of being heard. Audibility of sounds depends on level, frequency content, and can be reduced in the presence of other sounds (Morfey 2001)

Audiogram: A graph depicting hearing threshold as a function of frequency (ANSI 1995; Yost 2007) (Figure E1).

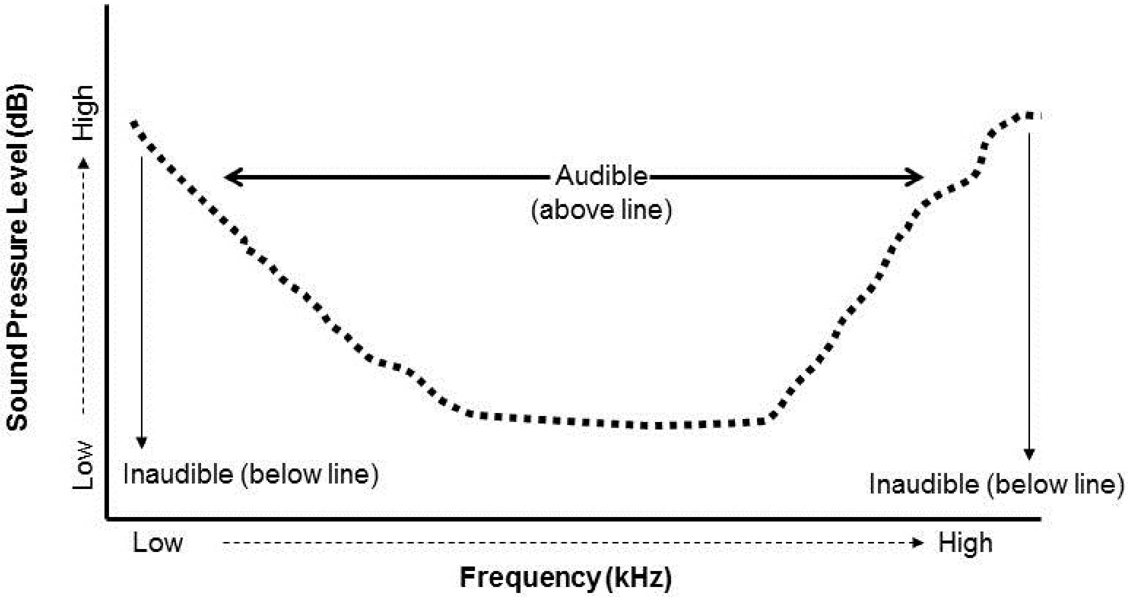

Figure E1. Example audiogram.

Auditory adaptation: Temporary decrease in hearing sensitivity occurring during the presentation of an acoustic stimulus (opposed to auditory fatigue which occurs post-stimulation) (ANSI 1995).

Auditory bulla: The ear bone in odontocetes that houses the middle ear structure (Perrin et al. 2009).

Auditory weighting function: Auditory weighting functions take into account what is known about marine mammal hearing sensitivity and susceptibility to noise-induced hearing loss and can be applied to a sound-level measurement to account for frequency-dependent hearing (i.e.,. an expression of relative loudness as perceived by the ear)(Southall et al. 2007; Finneran 2016). Specifically, this function represents a specified frequency-dependent characteristic of hearing sensitivity in a particular animal, by which an acoustic quantity is adjusted to reflect the importance of that frequency dependence to that animal (ISO 2017). Similar to OSHA (2013), marine mammal auditory weighting functions in this document are used to reflect the risk of noise exposure on hearing and not necessarily capture the most sensitive hearing range of every member of the hearing group.

Background noise: Total of all sources of interference in a system used for the production, detection, measurement, or recording of a signal, independent of the presence of the signal (ANSI 2013).

Band-pass filter: A filter that passes frequencies within a defined range without reducing amplitude and attenuates frequencies outside that defined range (Yost 2007).

Bandwidth: Bandwidth (Hz or kHz) is the range of frequencies over which a sound occurs or upper and lower limits of frequency band (ANSI 2005). Broadband refers to a source that produces sound over a broad range of frequencies (for example, seismic airguns), while narrowband or tonal sources produce sounds over a more narrow frequency range, typically with a spectrum having a localized a peak in amplitude (for example, sonar) (ANSI 1986; ANSI 2005).

Bone conduction: Transmission of sound to the inner ear primarily by means of mechanical vibration of the cranial bones (ANSI 1995).

Broadband: See “bandwidth”.

Cetacean: Any number of the order Cetacea of aquatic, mostly marine mammals that includes whales, dolphins, porpoises, and related forms; among other attributes they have a long tail that ends in two transverse flukes (Perrin et al. 2009).

Cochlea: Spirally coiled, tapered cavity within the temporal bone, which contains the receptor organs essential to hearing (ANSI 1995). For cetaceans, based on cochlear measurements two cochlea types have been described for echolocating odontocetes (type I and II) and one cochlea type for mysticetes (type M). Cochlea type I is found in species like the harbor porpoise and Amazon river dolphin, which produce high-frequency echolocation signals. Cochlea type II is found in species producing lower frequency echolocation signals (Ketten 1992).

Continuous sound: A sound whose sound pressure level remains above ambient sound during the observation period (ANSI 2005).

Critical level: The level at which damage switches from being primarily metabolic to more mechanical; e.g., short duration of impulse can be less than the ear’s integration time, leading for the potential to damage beyond level the ear can perceive (Akay 1978).

Cumulative sound exposure level (SEL_{cum}; re: 1μPa^{2}s): Level of acoustic energy accumulated over a given period of time or event (EPA 1982) or specifically, ten times the logarithm to the base ten of the ratio of a given time integral of squared instantaneous frequency-weighted sound pressure over a stated time interval or event to the reference sound exposure (ANSI 1995; ANSI 2013). Within the Technical Guidance, this metric is weighted based on the document’s marine mammal auditory weighting functions.

Deafness: A condition caused by a hearing loss that results in the inability to use auditory information effectively for communication or other daily activities (ANSI 1995).

Decibel (dB): One-tenth of a bel. Unit of level when the base of the logarithm is the tenth root of ten, and the quantities concerned are proportional to power (ANSI 2013).

dB/decade: This unit is typically used to describe roll-off, where a decade is a 10-times increase in frequency (roll-off can also be described as decibels per octave, where an octave is 2-times increase in frequency)

Duty cycle: On/off cycle time or proportion of time signal is active (calculated by: pulse length x repetition rate). A continuous sound has a duty cycle of 1 or 100%.

Dynamic range of auditory system: Reflects the range of the auditory system from the ability to detect a sound to the amount of sound tolerated before damage occurs (i.e., the threshold of pain minus the threshold of audibility) (Yost 2007). For the purposes of this document, the intent is relating the threshold of audibility and TTS onset levels, not the threshold of pain.

Effective quiet: The maximum sound pressure level that will fail to produce any significant threshold shift in hearing despite duration of exposure and amount of accumulation (Ward et al. 1976; Ward 1991).

Endangered Species Act (ESA): The Endangered Species Act of 1973 (16. U.S.C 1531 et. seq.) provides for the conservation of species that are endangered or threatened throughout all or a significant portion of their range, and the conservation of the ecosystems on which they depend.

NOAA's National Marine Fisheries Service and the U.S. Fish and Wildlife Service (USFWS) share responsibility for implementing the ESA.

Energy Source Level (SL_E): The time-integrated squared signal sound pressure level measured in a given radian direction, corrected for absorption, and scaled to a reference distance (1 m) (adapted from Morfey 2001).

Equal Energy Hypothesis (EEH): Assumption that sounds of equal energy produce the equal risk for hearing loss (i.e., if the cumulative energy of two sources are similar, a sound from a lower level source with a longer exposure duration may have similar risks to a shorter duration exposure from a higher level source) (Henderson et al. 1991).

Equal latency: A curve that describe the frequency-dependent relationships between sound pressure level and reaction time and are similar in shape to equal loudness contours in humans (loudness perception can be studied under the assumption that sounds of equal loudness elicit equal reaction times; e.g., Liebold and Werner 2002).

Equal-loudness contour: A curve or curves that show, as a function of frequency, the sound pressure level required to cause a given loudness for a listener having normal hearing, listening to a specified kind of sound in a specified manner (ANSI 2013).

Far-field: The acoustic field sufficiently distant from a distributed source that the sound pressure decreases linearly with increasing distance (neglecting reflections, refraction, and absorption) (ANSI 2013).

Fitness: Survival and lifetime reproductive success of an individual.

Frequency: The number of periods occurring over a unit of time (unless otherwise stated, cycles per second or hertz) (Yost 2007).

Functional hearing range: There is no standard definition of functional hearing arrange currently available. “Functional” refers to the range of frequencies a group hears without incorporating non-acoustic mechanisms (Wartzok and Ketten 1999). Southall et al. 2007 defined upper and lower limits of the functional hearing range as ~60-70 dB above the hearing threshold at greatest hearing sensitivity (based on human and mammalian definition of 60 dB[72]).

Fundamental frequency: Frequency of the sinusoid that has the same period as the periodic quantity (Yost 2007; ANSI 2013). First harmonic of a periodic signal (Morfey 2001).

Harmonic: A sinusoidal quantity that has a frequency which is an integral multiple of the fundamental frequency of the periodic quantity to which it is related (Yost 2007; ANSI 2013).

Hearing loss growth rates: The rate of threshold shift increase (or growth) as decibel level or exposure duration increase (expressed in dB of temporary threshold shift/dB of noise).Growth rates of threshold shifts are higher for frequencies where hearing is more sensitive (Finneran and Schlundt 2010). Typically in terrestrial mammals, the magnitude of a threshold shift increases with increasing duration or level of exposure, until it becomes asymptotic (growth rate begins to level or the upper limit of TTS; Mills et al. 1979; Clark et al. 1987; Laroche et al. 1989; Yost 2007).

Hertz (Hz): Unit of frequency corresponding to the number of cycles per second. One hertz corresponds to one cycle per second.

Impulsive sound: Sound sources that produce sounds that are typically transient, brief (less than 1 second), broadband, and consist of high peak sound pressure with rapid rise time and rapid decay (ANSI 1986; NIOSH 1998; ANSI 2005). They can occur in repetition or as a single event. Examples of impulsive sound sources include: explosives, seismic airguns, and impact pile drivers.

Information Quality Guidelines (IQG): Section 515 of the Treasury and General Government Appropriations Act for Fiscal Year 2001 (Public Law 106-554), directs the Office of Management and Budget (OMB) to issue government-wide guidelines that “provide policy and procedural guidance to federal agencies for ensuring and maximizing the quality, objectivity, utility, and integrity of information (including statistical information) disseminated by federal agencies.” OMB issued guidelines directing each federal agency to issue its own guidelines. Link to NOAA's Information Quality Guidelines

Integration time (of the ear): For a signal to be detected by the ear, it must have some critical amount of energy. The process of summing the power to generate the required energy is completed over a particular integration time. If the duration of a signal is less than the integration time required for detection, the power of the signal must be increased for it to be detected by the ear (Yost 2007).

Intermittent sound: Interrupted levels of low or no sound (NIOSH 1998) or bursts of sounds separated by silent periods (Richardson and Malme 1993). Typically, intermittent sounds have a more regular (predictable) pattern of bursts of sounds and silent periods (i.e., duty cycle).

Isopleth: A line drawn through all points having the same numerical value. In the case of sound, the line has equal sound pressure or exposure levels.

Kurtosis: Statistical quantity that represents the impulsiveness (“peakedness”) of the event; specifically the ratio of fourth- order central moment to the squared second-order central moment (Hamernik et al. 2003; Davis et al. 2009).

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[72] In humans, functional hearing is typically defined as frequencies at a threshold of 60 to 70 dB and below (Masterson et al. 1969; Wartzok and Ketten 1999), with normal hearing in the most sensitive hearing range considered 0 dB (i.e., 60 to 70 dB above best hearing sensitivity).

Linear interpolation: A method of constructing new data points within the range of a discrete set of known data points, with linear interpolation being a straight line between two points.

Marine Mammal Protection Act (MMPA): The Marine Mammal Protection Act (16. U.S.C. 1361 et. seq.)was enacted on October 21, 1972 and MMPA prohibits, with certain exceptions, the "take" of marine mammals in U.S. waters and by U.S. citizens on the high seas, and the importation of marine mammals and marine mammal products into the United States. NOAA's National Marine Fisheries Service and the U.S. Fish and Wildlife Service (USFWS) share responsibility for implementing the MMPA.

Masking: Obscuring of sounds of interest by interfering sounds, generally of the similar frequencies (Richardson et al. 1995).

Mean-squared error (MSE): In statistics, this measures the average of the squares of the "errors," that is, the difference between the estimator and what is estimated.

Mean-square sound pressure: Integral over a specified time interval of squared sound pressure, divided by the duration of the time interval for a specified frequency range (ISO 2017).

Multipath propagation: This phenomenon occurs whenever there is more than one propagation path between the source and receiver (i.e., direct path and paths from reflections off the surface and bottom or reflections within a surface or deep-ocean duct; Urick 1983).

Mysticete: The toothless or baleen (whalebone) whales, including the rorquals, gray whale, and right whale; the suborder of whales that includes those that bulk feed and cannot echolocate (Perrin et al. 2009).

Narrowband: See "bandwidth".

National Marine Sanctuaries Act (NMSA): The National Marine Sanctuaries Act (16 U.S.C. 1431 et. seq.) authorizes the Secretary of Commerce to designate and protect areas of the marine environment with special national significance due to their conservation, recreational, ecological, historical, scientific, cultural, archeological, educational, or esthetic qualities as national marine sanctuaries. Day-to-day management of national marine sanctuaries has been delegated by the Secretary of Commerce to NOAA's Office of National Marine Sanctuaries.

National Standard 2 (NS2): The Magnuson-Stevens Fishery Conservation and Management Act (MSA) (16 U.S.C. 1801 et. seq.) is the principal law governing marine fisheries in the U.S. and includes ten National Standards to guide fishery conservation and management. One of these standards, referred to as National Standard 2 (NS2), guides scientific integrity and states "(fishery) conservation and management measures shall be based upon the best scientific information available.

Non-impulsive sound: Sound sources that produce sounds that can be broadband, narrowband or tonal, brief or prolonged, continuous or intermittent) and typically do not have a high peak sound pressure with rapid rise time that impulsive sounds do. Examples of non-impulsive sound sources include: marine vessels, machinery operations/construction (e.g., drilling), certain active sonar (e.g. tactical), and vibratory pile drivers.

Octave: The interval between two sounds having a basic frequency ratio of two (Yost 2007). For example, one octave above 400 Hz is 800 Hz. One octave below 400 Hz is 200 Hz.

Odontocete: The toothed whales, including sperm and killer whales, belugas, narwhals, dolphins and porpoises; the suborder of whales including those able to echolocate (Perrin et al. 2009).

Omnidirectional: Receiving or transmitting signals in all directions (i.e., variation with direction is designed to be as small as possible).

One-third octave (base 10): The frequency ratio corresponding to a decidecade or one tenth of a decade (ISO 2017).

Otariid: The eared seals (sea lions and fur seals), which use their foreflippers for propulsion (Perrin et al. 2009).

Peak sound pressure level (PK; re: 1 µPa): The greatest magnitude of the sound pressure, which can arise from a positive or negative sound pressure, during a specified time, for a specific frequency range (ISO 2017).

Perception: Perception is the translation of environmental signals to neuronal representations (Dukas 2004).

Permanent threshold shift (PTS): A permanent, irreversible increase in the threshold of audibility at a specified frequency or portion of an individual's hearing range above a previously established reference level. The amount of permanent threshold shift is customarily expressed in decibels (ANSI 1995; Yost 2007). Available data from humans and other terrestrial mammals indicate that a 40 dB threshold shift approximates PTS onset (see Ward et al. 1958, 1959; Ward 1960; Kryter et al. 1966; Miller 1974; Ahroon et al. 1996; Henderson et al. 2008).

Phocid: A family group within the pinnipeds that includes all of the "true" seals (i.e. the "earless" species). Generally used to refer to all recent pinnipeds that are more closely related to *Phoca* than to otariids or the walrus (Perrin et al. 2009).

Pinniped: Seals, sea lions and fur seals (Perrin et al. 2009).

Pulse duration: For impulsive sources, window that makes up 90% of total cumulative energy (5%-95%) (Madsen 2005)

Propagation loss: Reduction in magnitude of some characteristic of a signal between two stated points in a transmission system (for example the reduction in the magnitude of a signal between a source and a receiver) (ANSI 2013).

Received level: The level of sound measured at the receiver.

Reference pressure: See sound pressure level.

Repetition rate: Number of pulses of a repeating signal in a specific time unit, normally measured in pulses per second.

Rise time: The time interval a signal takes to rise from 10% to 90% of its highest peak (ANSI 1986; ANSI 2013).

Roll-off: Change in weighting function amplitude (-dB) with changing frequency.

Root-mean-square sound pressure level (RMS SPL; re: 1 µPa): Ten times the logarithm to the base 10 of the ratio of the mean-square sound pressure to the specified reference value in decibels (ISO 2017).

Sensation level (dB): The pressure level of a sound above the hearing threshold for an individual or group of individuals (ANSI 1995; Yost 2007).

Sound: An alteration in pressure propagated by the action of elastic stresses in an elastic medium and that involves local compression and expansion of the medium (ISO 2017).

Sound Exposure Level (SEL_{cum}; re: 1µPa^{2}s): A measure of sound level that takes into account the duration of the signal. Ten times the logarithm to the base 10 of the ration of a given time integral of squared instantaneous frequency-weighted sound pressure over a stated time interval or event to the product of the squared reference sound pressure and reference duration of one second (ANSI 2013).

Sound Pressure Level (SPL): A measure of sound level that represents only the pressure component of sound. Ten times the logarithm to the base 10 of the ratio of time-mean-square pressure of a sound in a stated frequency band to the square of the reference pressure (1 µPa in water) (ANSI 2013).

Source Level (SL): Sound pressure level measured in a given radian direction, corrected for absorption, and scaled to a reference distance (Morfey 2001). For underwater sources, the sound pressure level of is measured in the far-field and scaled to a standard reference distance (1 meter) away from the source (Richardson et al. 1995; ANSI 2013).

Spatial: Of or relating to space or area.

Spectral/spectrum: Of or relating to frequency component(s) of sound. The spectrum of a function of time is a description of its resolution into components (frequency, amplitude, etc.). The spectrum level of a signal at a particular frequency is the level of that part of the signal contained within a band of unit width and centered at a particular frequency (Yost 2007).

Spectral density levels: Level of the limit, as the width of the frequency band approaches zero, of the quotient of a specified power-like quantity distributed within a frequency band, by the width of the band (ANSI 2013).

Subharmonic: Sinusoidal quantity having a frequency that is an integral submultiple of the fundamental frequency of a periodic quantity to which it is related (ANSI 2013).

Temporal: Of or relating to time.

Temporary threshold shift (TTS): A temporary, reversible increase in the threshold of audibility at a specified frequency or portion of an individual's hearing range above a previously established reference level. The amount of temporary threshold shift is customarily expressed in decibels (ANSI 1995, Yost 2007). Based on data from cetacean TTS measurements (see Southall et al. 2007 for a review), a TTS of 6 dB is considered the minimum threshold shift clearly larger than any day-to-day or session-to-session variation in a subject's normal hearing ability (Schlundt et al. 2000; Finneran et al. 2000; Finneran et al. 2002).

Threshold (of audibility): The threshold of audibility (auditory threshold) for a specified signal is the minimum effective sound pressure level of the signal that is capable of evoking an auditory sensation in a specified fraction of trials (either physiological or behavioral) (Yost 2007). It recommended that this threshold be defined as the lowest sound pressure level at which responses occur in at least 50% of ascending trials. (ANSI 2009).

Threshold shift: A change, usually an increase, in the threshold of audibility at a specified frequency or portion of an individual's hearing range above a previously established reference level. The amount of threshold shift is customarily expressed in decibels (ANSI 1995, Yost 2007).

Tone: A sound wave capable of exciting an auditory sensation having pitch. A pure tone is a sound sensation characterized by a single pitch (one frequency). A complex tone is a sound sensation characterized by more than one pitch (more than one frequency) (ANSI 2013).

Uncertainty: Lack of knowledge about a parameter’s true value (Bogen and Spears 1987; Cohen et al. 1996).

Variability: Differences between members of the populations that affects the magnitude of risk to an individual (Bogen and Spears 1987; Cohen et al. 1996; Gedamke et al. 2011).

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Marine Mammal Noise Exposure Criteria: Initial Scientific Recommendations

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Contents

Acronyms

Acronym	Definition
A-weighting	Frequency-selective weighting for aerial hearing in humans derived from the inverse of the idealized 40-phon equal loudness hearing function across frequencies
ABR	Auditory brainstem response
ADD	Acoustic deterrent device
AEP	Auditory evoked potentials
AHD	Acoustic harassment device
ANSI	American National Standards Institute
ASSR	Auditory steady-state response
ATOC	Acoustic Thermometry of Ocean Climate program
CF	Center frequency
C-weighting	Frequency-selective weighting for aerial hearing in humans derived from the inverse of the idealized 100-phon equal loudness hearing function across frequencies
EFR	Envelope following response
EPA	U.S. Environmental Protection Agency
ES	Explosion simulator
f_{high}	Estimated upper functional hearing limit
f_{low}	Estimated lower functional hearing limit
HESS	High Energy Seismic Survey
HPA	Hypothalamic-pituitary-adrenal axis
IMAPS	Integrated Marine Mammal Monitoring and Protection System
ISO	International Standards Organization
JNCC	U.K. Joint Nature Conservation Committee
L_{eqT}	Equivalent-continuous sound level over period T
L_{IeqT}	Impulse equivalent-continuous sound level over period T
LFA	Low Frequency Active (sonar)
M-weighting	Generalized frequency weightings for various groups of marine mammals, allowing for their functional bandwidths and appropriate in characterizing auditory effects of strong sounds
M_{lf}	Frequency weighting for low-frequency cetaceans (mysticetes)
M_{mf}	Frequency weighting for mid-frequency cetaceans (most odontocetes)
M_{hf}	Frequency weighting for high-frequency cetaceans (odontocetes specialized for use of very high frequencies)
M_{pw}	Frequency weighting for pinnipeds, listening in water
M_{pa}	Frequency weighting for pinnipeds, listening in air
MMPA	U.S. Marine Mammal Protection Act
NIHL	Noise-induced hearing loss
NIPTS	Noise-induced permanent threshold shift
NIOSH	U.S. National Institute for Occupational Safety and Health
NMFS	U.S. National Marine Fisheries Service

Acronym	Definition
NOAA	U.S. National Oceanic and Atmospheric Administration
NRC	U.S. National Research Council
NRL	U.S. Naval Research Laboratory
P_{max}	Maximum sound pressure
OBN	Octave-band noise
PCAD	National Research Council's Population Consequences of Acoustic Disturbance Model
PICE	Porpoise incidental catch elimination
PTS	Permanent threshold shift
REFMS	A computer program for predicting shock-wave propagation from underwater explosions
RL	Received level
RMS	Root-mean-square
SEL	Sound exposure level
SL	Source level (received level measured or estimated 1 m from the source)
SLM	Sound level meter
SPL	Sound pressure level
TS	Threshold shift
TTS	Temporary threshold shift
USC	United States Code
VAFB	Vandenberg Air Force Base

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Overview

A group of experts in acoustic research from behavioral, physiological, and physical disciplines was convened over a several year period. The purpose of this panel was to review the expanding literature on marine mammal hearing and on physiological and behavioral responses to anthropogenic sound, and to propose exposure criteria for certain effects. The group employed all available relevant data to predict noise exposure levels above which adverse effects on various groups of marine mammals are expected. Recent advances in these fields and the pressing need for a science-based paradigm to assess the effects of sound exposure were the primary motivations for this effort. Two categories of effects were considered: (1) injury and (2) behavioral disturbance. The proposed criteria for the onset of these effects were further segregated according to the functional hearing capabilities of different marine mammal groups, and according to the different categories and metrics of typical anthropogenic sounds in the ocean. The group achieved many of its objectives but acknowledges certain limitations in the proposed criteria because of scarcity or complete absence of information about some key topics. A major component of these recommendations is a call for specific research on critical topics to reduce uncertainty and improve future exposure criteria for marine mammals. This publication marks the culmination of a long and challenging initial effort, but it also initiates a necessary, iterative process to apply and refine noise exposure criteria for different species of marine mammals.

The process of establishing policy guidelines or regulations for anthropogenic sound exposure (i.e., the application of these exposure criteria) will vary among nations, jurisdictions, and legal/policy settings. Such processes should carefully consider the limitations and caveats given with these proposed criteria in deciding whether sufficient data currently exist to establish simplistic, broad criteria based solely on exposure levels. In many cases, especially for behavioral disturbance, context-specific analyses considering previous studies on species and conditions similar to those in question might, at least for the foreseeable future, be more appropriate than general guidelines.

State of Current Knowledge

The available data on the effects of noise on marine mammals are quite variable in quantity and quality. In many respects, data gaps severely restrict the derivation of scientifically-based noise exposure criteria and, in some cases, explicit threshold criteria for certain effects are not appropriate given the amount and type of data available. Scientific inquiry into acoustic communication among marine mammals extends back more than half a century, but most of the specific data relevant to the proposed criteria have been published within the last two decades. Owing to the mounting public, scientific, and regulatory interest in conservation issues related to acoustics, the available science is progressing rapidly (e.g., see NRC, 2003, 2005).

This paper proposes, for various marine mammal groups and sound types, levels above which there is a scientific basis for expecting that exposure would cause auditory injury to occur. Controlled measurements of hearing and of the effects of underwater and aerial sound in laboratory settings have greatly expanded the ability to assess auditory effects. While understanding of the hearing capacities among all marine mammals remains admittedly rudimentary, there is a fairly detailed understanding of some key aspects of underwater and aerial hearing in a few representative species of odontocetes, pinnipeds, and sirenians, although hearing in mysticetes remains untested. Available data, along with the compelling evidence of similar auditory processes among all mammals, enables some reasonable extrapolations across species for estimating auditory effects, including the exposure levels of probable onset of injury. Recent evidence suggests that exposure of beaked whales to underwater noise may, under certain (generally unknown) conditions, result in non-auditory injury as well (e.g., Fernández et al., 2005). At present, however, there are insufficient data to allow formulation of quantitative criteria for non-auditory injuries.

There are many more published accounts of behavioral responses to noise by marine mammals than of direct auditory or physiological effects. Nevertheless, the available data on behavioral responses do not converge on specific exposure conditions resulting in particular reactions, nor do they point to a common behavioral mechanism. Even data obtained with substantial controls, precision, and standardized metrics indicate high variance both in behavioral responses and in exposure conditions required to elicit a given response. It is clear that behavioral responses are strongly affected by the context of exposure and by the animal's experience, motivation, and conditioning. This reality, which is generally consistent with patterns of behavior in other mammals (including humans), hampered our efforts to formulate broadly applicable behavioral response criteria for marine mammals based on exposure level alone.

Frequency-Weighting Functions

In humans, hearing processes in a large number of male and female subjects of different ages have been tested to determine a basic audiometric curve, equal-loudness curve, and the levels and exposure durations needed to induce either recoverable hearing loss (called temporary threshold shift or TTS) or permanent threshold shift (PTS). In addition, the manner in which successive exposures to noise contribute to TTS growth has been well-documented in humans (e.g., Kryter, 1994; Ward, 1997). In assessing the effects of noise on humans, either an A- or C-weighted curve is applied to correct the sound-level measurement for the frequency-dependent hearing function of humans. Early on, the panel recognized that similar, frequency-weighted hearing curves were needed for marine mammals; otherwise, extremely low- and high-frequency sound sources that are detected poorly, if at all, might be subject to unrealistic criteria.

One of the major accomplishments in this effort was the derivation of recommended frequency-weighting functions for use in assessing the effects of relatively intense sounds on hearing in some marine mammal groups. It is abundantly clear from measurements of marine mammal hearing in the laboratory, call characteristics, and auditory morphology that there are major differences in auditory capabilities across marine mammal species (e.g., Wartzok & Ketten, 1999). Most previous assessments of acoustic effects either failed to account for differences in functional hearing bandwidth among marine mammal groups or did not recognize that the "nominal" audiogram might be a relatively poor predictor of how the auditory system responds to relatively strong exposures.

The authors delineated five groups of marine mammals based on similarities in their hearing, and they developed a generalized frequency-weighting (called "M-weighting") function for each. The five groups and the associated designators are (1) mysticetes (baleen whales), designated as "low-frequency" cetaceans (M_{lf}); (2) some odontocetes (toothed whales), designated as "mid-frequency" cetaceans (M_{mf}); (3) odontocetes specialized for using high frequencies (i.e., porpoises, river dolphins, and the genera *Kogia* and *Cephalorhynchus*) (M_{hf}); (4) pinnipeds (i.e., seals, sea lions, and walruses) listening in water (M_{pw}); and (5) pinnipeds listening in air (M_{pa}). These criteria do not specifically address sirenians, the sea otter, or the polar bear, in part because of the lack of key data in these species.

The M-weighting functions were defined based on known or estimated auditory sensitivity at different frequencies rather than vocal characteristics per se. Owing to the paucity of relevant data, these auditory functions are intentionally precautionary (wide) and likely overestimate the functional bandwidth for most or all species. Their primary application is in predicting auditory damage rather than levels of detection or behavioral response. Consequently, it is more appropriate to use "flatter" functions than would be obtained by employing a simple inverse-audiogram function.

Exposure Criteria Metrics

To further complicate the derivation of noise exposure criteria, sounds can be described with various acoustic metrics, including sound pressure levels and sound exposure levels. The latter is a measure of received sound energy. Available literature provides a mixture of both measures, but many sound sources have primarily been described in pressure level units. To accommodate these two measures, and to account for all relevant acoustic features that may affect marine mammals, we developed dual criteria for noise exposures in each of the five functional hearing groups, using both sound pressure and sound exposure levels.

Exposure Criteria for Injury

Another area in which we provide substantive conclusions is in the determination of sound exposures believed to cause direct auditory injury to marine mammals. By all accounts, the inner ear is the organ system most directly sensitive to sound exposure and, thus, the most susceptible to sound-derived damage. We define the minimum exposure criterion for injury as the level at which a single exposure is estimated to cause onset of permanent hearing loss (PTS). Data on TTS in marine mammals, and on patterns of TTS growth and its relation to PTS in other mammals, were used to estimate thresholds for injury. Owing to the limited availability of relevant data on TTS and PTS, the extrapolation procedures underlying these estimations are necessarily precautionary.

To account for all of the potentially injurious aspects of exposure, dual criteria for injury were established for each functional marine mammal hearing group based on instantaneous peak pressure (unweighted) and total energy (M-weighted). Exposure criteria for injury are given for two types of sounds, pulse and nonpulse, and for single and multiple exposures. The term *pulse* is used here to describe brief, broadband, atonal, transients (ANSI, 1986; Harris, 1998, Chapter 12), which are characterized by a relatively rapid rise-time to maximum pressure followed by a decay that may include a period of diminishing and oscillating maximal and minimal pressures. Examples of pulses are sounds from explosions, gunshots, sonic booms, seismic airgun pulses, and pile driving strikes. Nonpulse (intermittent or continuous) sounds can be tonal, broadband, or both. They may be of short duration but without the essential properties of pulses (e.g., rapid rise-time). Examples of anthropogenic, oceanic sources producing such sounds include vessels, aircraft, machinery operations such as drilling or wind turbines, and many active sonar systems. As a result of propagation, sounds with the characteristics of a pulse at the source may lose pulsatile characteristics at some (variable) distance and can be characterized as a nonpulse by certain receivers.

Regardless of the anthropogenic sound, if a marine mammal's received exposures exceed the relevant (pulse or nonpulse) criterion, auditory injury (PTS) is assumed to be likely. Chapter 3, "Criteria for Injury," provides details regarding the exposure levels required to cause TTS-onset and the extrapolation of those results to estimate levels above which PTS-onset may occur. For all five functional hearing groups, we propose dual exposure criteria above which auditory injury is likely.

Exposure Criteria for Behavior

One challenge in developing behavioral criteria is to distinguish a significant behavioral response from an insignificant, momentary alteration in behavior. For example, the startle response to a brief, transient event is unlikely to persist long enough to constitute significant disturbance. Even strong behavioral responses to single pulses, other than those that may secondarily result in injury or death (e.g., stampeding), are expected to dissipate rapidly enough as to have limited long-term consequence. Consequently, upon exposure to a single pulse, the onset of significant behavioral disturbance is proposed to occur at the lowest level of noise exposure that has a measurable transient effect on hearing (i.e., TTS-onset). We recognize that this is not a behavioral effect per se, but we use this auditory effect as a *de facto* behavioral threshold until better measures are identified. Lesser exposures to a single pulse are not expected to cause significant disturbance, whereas any compromise, even temporarily, to hearing functions has the potential to affect vital rates through altered behavior.

For other anthropogenic sound types (multiple pulses, nonpulses), we conducted an extensive review of the available literature but were unable to derive explicit and broadly applicable numerical threshold values for delineating behavioral disturbance. We did develop a quantitative scoring paradigm that numerically ranks, as a severity scaling, behavioral responses observed in either field or laboratory conditions. We applied this approach to the appropriate behavioral data for multiple pulses and nonpulses. Some of these data suffer from poor statistical power, limited information on received sound levels and background noise, insufficient measurements of all potentially important contextual variables, and/or insufficient controls. Some such data are analyzed here solely for illustrative purposes. Most behavioral studies suffered from at least some of these problems. Therefore, we do not intend to give uniform scientific credence to all of the cited data, and we expect future studies to give greater attention and rigor to these critical requirements.

This review and scoring process, while not a formal meta-analysis for normalizing and pooling disparate observations, corroborated certain interesting aspects of marine mammal behavioral responses to sound exposure. Foremost was that a behavioral response is determined not only by simple acoustic metrics, such as received level (RL), but also by contextual variables (e.g., laboratory vs field conditions, animal activity at the time of exposure, habituation/sensitization to the sound, etc.). Also important is 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). Within certain similar conditions, there appears to be some relationship between the exposure RL and the magnitude of behavioral response. However, in many cases, such relationships clearly do not exist, at least when response data are pooled across multiple species and contexts. This argues for a context-based approach to deriving noise exposure criteria for behavioral responses. That concept, along with our review and scaling of the available observational data, provides a foundation for establishing dose-response relationships for some specific circumstances and a starting point for future analyses when additional data are available.

Conclusions and Research Recommendations

This process has resulted in several significant advances. These include a review and interpretation of the available literature on injury and behavioral data using precautionary extrapolation procedures, derivation of marine mammal frequency-weighting functions, specification of quantitative criteria for auditory injury, and derivation of a "severity scale" for behavioral responses.

The inability to identify broadly applicable, quantitative criteria for behavioral disturbance in response to multiple-pulse and nonpulse sounds is an acknowledged limitation.

Our efforts to derive marine mammal noise exposure criteria clearly illustrate the fact that, at present, research in this field remains limited in many areas. The need for extrapolation procedures and precautionary assumptions points directly to research needs in a variety of areas on a variety of species. In certain conditions, proposed criteria for an entire marine mammal group are based on the most precautionary measurement or observation for a species within that group, despite the fact that, for other species within that group, there are empirical data indicating that higher exposures are required to induce the same effect. We believe it is appropriate to use the most precautionary data in proposing group-wide criteria applicable for species where there are no direct measurements. We also feel it is appropriate on a case-by-case basis to apply the most relevant empirical data (i.e., from the species or genus of concern) in setting the exposure thresholds specified in policy guidelines.

Finally, we emphasize that exposure criteria for single individuals and relatively short-term (not chronic) exposure events, as discussed here, are insufficient to describe the cumulative and ecosystem-level effects likely to result from repeated and/or sustained human input of sound into the marine environment and from potential interactions with other stressors. Also, the injury criteria proposed here do not appear to predict what may have been indirect injury from acoustic exposure in several cases where cetaceans of several species mass-stranded following exposure to military sonar.

The extensive research recommendations given here (see Chapter 5) represent our collective view of the concerted effort that will be required over the coming decades. High priority categories of research include (1) continued expansion of knowledge on basic marine mammal hearing capabilities, including sound localization, the detection of realistic sound signals, communication masking, and auditory "scene analysis"; (2) continued expansion of knowledge on baseline marine mammal behavioral patterns; (3) well-controlled, direct measurements (using appropriate, standardized acoustic metrics) of the effects of sound exposure on marine mammal hearing, behavior, and physiology; and (4) risk-assessment studies of the cumulative and synergistic effects of noise and other exposure(s) on individuals and populations.

Understanding and managing the effects of noise on marine life without unjustifiably constraining important human activities in the oceans will continue to be challenging for the foreseeable future. With sustained and focused research in key areas, future scientists will be equipped to make informed improvements to the initial scientific recommendations presented here. These improvements should ideally be integrated into science-based risk assessment models that consider all aspects of sound exposure and other potential stressors on individual marine mammals, populations, and marine ecosystems.

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1. Introduction

Objectives

Recent interest and concern about the effects of anthropogenic noise on marine mammals has triggered considerable new research (e.g., Costa et al., 2003; Fristrup et al., 2003; Finneran et al., 2005a), summaries of available information (Richardson et al., 1995; Wartzok & Ketten, 1999), and recommendations for specific action (NRC, 1994, 2000, 2003, 2005). Systematic, objective, science-based interpretation of the available data is critically needed to inform management agencies charged with mitigating adverse effects of anthropogenic noise on protected species. In response to this need, we use here the full body of scientific data on marine mammal hearing and the effects of noise on hearing and behavior, augmented where appropriate by interpretations of terrestrial mammal (including human) data, to develop proposed exposure criteria that are as comprehensive, defensible, and precise as is currently possible. The scope of these criteria includes injurious and behavioral effects of a single noise exposure event on an individual cetacean (whales, dolphins, and porpoises) or pinniped (seals, sea lions, and walruses).

The recommended noise exposure criteria are science-based, developed without addressing the commercial, societal, or practical ramifications of implementing the conclusions reached here. We intend to mirror the process used in the development of damage risk criteria for humans (see Crocker, 1997). Policy "guidelines" developed for regulatory and societal purposes are based both on scientific evidence (as summarized in this paper for marine mammals) and on other considerations (e.g., economic, practical, social, and ethical) not dealt with here. Thus, on certain points, policy guidelines that are developed separately for the purposes of various jurisdictions, nations, or users of these criteria may differ from the science-based criteria recommended here.

All forms of anthropogenic noise received by marine mammals were considered, whether produced under water or in air, and we adopted a comparative approach, which we regard as essential to any criteria-setting process for nonhuman animals. For most of the ~128 marine mammal species and subspecies (Rice, 1998) considered here, no empirical data were available on nominal hearing characteristics or on the effects of noise on hearing or behavior. Practical, ethical, and legal considerations limit the level of scientific information that is available for deriving criteria applicable to either humans or marine mammals. Consequently, certain assumptions and criteria proposed here were based on information from other mammalian groups, where justified. Where such data present a variety of options, we made intentionally precautionary decisions (i.e., lower proposed exposure levels) to reduce the risk of assuming no effect when one was actually present. The term "precautionary" is used here without reference to any regulatory or policy implication of this word. Scientists would more conventionally use the term "conservative" in this regard rather than the more bureaucratic "precautionary," but in certain complex instances here, the term "conservative" would be potentially ambiguous, depending on the perspective of the reader. When information was limited, extrapolations were made cautiously to minimize the risk of failing to recognize an effect when one actually occurs (Type-II statistical error) as can occur with small sample sizes or imprecise measurements.

Each generalization/extrapolation was identified, all precautionary decisions were noted, and the logic leading to each proposed criterion was specified. Thus, when new data become available, appropriate modifications can be made readily. Studies that are needed to resolve the uncertainties encountered in developing the current criteria are discussed in detail (see Chapter 5, "Research Recommendations"). Realistically, however, the generalization of information between related species will remain essential in many cases for the foreseeable future.

Our intent was to derive recommended noise exposure criteria using the best information currently available, identify weaknesses in the present approach, call for relevant research, and structure the criteria such that future improvements can be incorporated easily. Lack of data limited the proposed noise exposure criteria to individual marine mammals exposed to acute exposure events (such as the passage of one vessel or a series of active sonar transmissions). Also, the proposed criteria are limited to cetaceans and pinnipeds. We expect that noise exposure criteria for other marine mammals (manatees, dugongs, polar bears, and sea otters), as well as other marine taxa, will be developed as additional data become available and are evaluated. In fact, a separate expert panel (S3/

WG92: "Effects of Sound on Fish and Turtles") has been established under the Standards Committee (S3) of the Acoustical Society of America to consider noise exposure criteria for fish and turtles. Additionally, criteria are clearly needed for cumulative effects and for effects at species or even ecosystem levels, but data to support those types of criteria do not currently exist.

The present recommended criteria represent a major step in initiating a lengthy, systematic process to predict and identify acoustic exposure conditions (natural or anthropogenic) associated with various effects on marine mammals. This paper is deliberately structured in a somewhat formulaic and report-like manner so that the logic underlying certain assumptions and extrapolations (as well as the data needed to test and/or strengthen them) is self-evident. We expect there will be an iterative process of improving and expanding the complexity of the exposure criteria, similar to the decades-long development of human noise exposure criteria (see Crocker, 1997). Because of the matrix structure of the proposed criteria, thresholds in specific cells can be updated independently as new information becomes available.

There is an extensive history and diversity of exposure criteria for humans with various kinds of acoustic exposure. A full discussion of these criteria is beyond the scope of this paper, but examples include workplace noise standards (e.g., NIOSH, 1998), standards for the protection of military personnel (U.S. DoD, 1997), and national policy guidelines (e.g., EPA, 1974; BG PPG, 1994). Several additional examples were also considered, whether received under water or in air, in various decisions underlying the marine mammal criteria proposed here. The process of establishing human noise exposure criteria has been difficult and contentious, but establishing noise exposure criteria for marine mammals is considerably more daunting given the diversity of marine mammal species across three orders, the complexity of aerial and underwater acoustic exposures, and profound data limitations.

Historical Perspective

Concerns about potential adverse effects of anthropogenic noise on marine life began in the 1970s (e.g., Payne & Webb, 1971) and expanded in the 1980s. Experiments during the 1980s with seismic airguns indicated that bowhead whales (*Balaena mysticetus*) and gray whales (*Eschrichtius robustus*) exhibited clear, sustained avoidance of operational areas at distances where pulse root-mean-square (RMS) sound pressure levels (SPLs) were 160 to 170 dB re: 1 µPa (Malme et al., 1983, 1984, 1986, 1988; Richardson et al., 1986; Ljungblad et al., 1988). In contrast, early observations of bowhead and gray whales exposed to continuous industrial sounds, such as those associated with drilling operations, suggested 120 dB re: 1 µPa as the approximate threshold for behavioral disturbance of these baleen whales (Malme et al., 1984; Richardson et al., 1990a, 1995 [pp. 286-287]). Significant individual variability was noted in "typical" behavioral responses, however, with some individual whales responding only when very close to sound sources and others reacting at much longer distances (and to lower received sound levels). This variability raises questions as to whether behavioral responses are most appropriately described by the exposure received level (RL) of the stimulus at the animal, the signal-to-ambient noise differential, the rate of change of the signal, or simply to the presence of the human activity as indicated by acoustic cues and/or visual stimuli.

Concern about the effects of acoustic pulses from seismic exploration and continuous sound from other industrial activities resulted in the imposition of mitigation requirements on some industrial activities in certain jurisdictions by the early- to mid-1980s. Subsequent events, such as the Heard Island Feasibility Test in 1991 (Baggeroer & Munk, 1992), the Acoustic Thermometry of Ocean Climate (ATOC) program in the late-1990s (see NRC, 1994, 2000; Au et al., 1997; Costa et al., 2003), and the U.S. Navy's low-frequency active sonar program (e.g., Croll et al., 2001) resulted in popular and governmental interest in setting criteria for safe levels of sound for marine mammal exposure (NRC, 1994, 2000, 2003; Richardson et al., 1995). This interest has expanded with the finding that tactical, mid-frequency, military sonar transmissions are sometimes correlated, in specific conditions, with mass stranding events of (predominantly) several beaked whale species, including Cuvier's (*Ziphius cavirostris*), Blainville's (*Mesoplodon densirostris*), and Gervais' (*Mesoplodon europaeus*) beaked whales (see Evans & England, 2001; Fernández et al., 2005; Cox et al., 2006).

In 1995, the U.S. National Marine Fisheries Service (NMFS) set underwater "do not exceed" criteria for exposure of marine mammals to underwater pulses from seismic airguns. These criteria were 190 dB re: 1 µPa for pinnipeds and most odontocete cetaceans and 180 dB re: 1 µPa for mysticetes and sperm whales (*Physeter macrocephalus*) (and, by inference, for pygmy and dwarf sperm whales [*Kogia* spp.]). These exposure limits were intended as precautionary estimates of exposures below which physical injury would not occur in these taxa. There was no empirical evidence as to whether exposure to higher levels of pulsed sounds would or would not cause auditory or other injuries. Given the limited data then available, however, it could not be guaranteed that marine mammals exposed to higher levels would not be injured. Further, it was recognized that behavioral disturbance could, and in some cases likely would, occur at lower RLs.

In June 1997, the High Energy Seismic Survey (HESS) team (1999, Appendix 5) convened a panel of experts to assess noise exposure criteria for marine mammals exposed to seismic pulses. The consensus was that, given the best available data at that time, exposure to airgun pulses with RLs above 180 dB re: 1 μPa (averaged over the pulse duration) was "likely to have the potential to cause serious behavioral, physiological, and hearing effects." The panel noted the potential for ± 10 dB variability around the 180 dB re: 1 μPa level, depending on species, and that more information was needed.

The NMFS has continued to use a "do not exceed" exposure criterion of 180 dB re: 1 μPa for mysticetes and (recently) all odontocetes exposed to sequences of pulsed sounds, and a 190 dB re: 1 μPa criterion for pinnipeds exposed to such sounds. Higher thresholds have been used in the U.S. for single pulses such as explosions used in naval vessel-shock trials. Behavioral disturbance criteria for pulsed sounds have typically been set at an SPL value of 160 dB re: 1 μPa, based mainly on the earlier observations of mysticetes reacting to airgun pulses (e.g., Malme et al., 1983, 1984; Richardson et al., 1986). The relevance of the 160 dB re: 1 μPa disturbance criterion for odontocetes and pinnipeds exposed to pulsed sounds is not at all well-established, however. Although these criteria have been applied in various regulatory actions (principally in the U.S.) for more than a decade, they remain controversial, have not been applied consistently in the U.S., and have not been widely accepted elsewhere.

More recently, a considerable body of data has accumulated on the levels at which transient and more prolonged sounds cause the onset of temporary threshold shift (TTS) and various behavioral reactions. Some of these data are not consistent with the aforementioned *de facto* criteria used in recent years in the United States.

One main purpose of this paper is to synthesize and apply all available information to derive proposed objective noise exposure criteria for a large subset of marine mammals. The effect levels considered (injury and significant behavioral disturbance) were generally consistent with the definitions of levels A and B harassment, respectively, of the U.S. Marine Mammal Protection Act (MMPA) of 1972 (16 USC, § 1361); however, many of the behaviors considered at the lower end of our severity scaling paradigm would almost certainly not constitute biologically significant disturbance (or consequently level B harassment under the MMPA). However, our exposure criteria were derived without regard for policy decisions of the U.S. or any nation and should therefore not be assumed to correspond with regulatory categories or definitions of effects. Since harassment definitions under the MMPA are not uniform for all human activities and are subject to change, additional interpretation of the information presented would be required to evaluate effects with regard to this (or any other) statute.

Acoustic Measures and Terminology

This section briefly considers those acoustic measures and terminology that are directly relevant to these marine mammal exposure criteria. More detailed descriptions of some of the terms given in this and other sections, including equations relevant to many of the definitions, are given in Appendix A. Basic acoustic terminology is presented in numerous other sources (e.g., Kinsler et al., 1982; ANSI, 1986, 1994; Richardson et al., 1995; Harris, 1998; NRC, 2003).

Sound is appropriately described as having two components: (1) a pressure component and (2) a particle motion component. Particle motion—the oscillatory displacement, velocity, or acceleration of the actual "particles" of the medium at a particular location—is directional and best described by a 3-dimensional vector. Marine mammal sensitivity to particle motion is poorly understood, but it appears to be functionally limited (Finneran et al., 2002a) in contrast to the sensory capabilities of most or all fish (see Popper et al., 2003). Conversely, as compared to fish, marine mammals generally have greater sensitivity to sound pressure (lower detection thresholds) and much wider functional hearing bandwidths (see Fay, 1988; Richardson et al., 1995; Popper et al., 2003). Consequently, in considering the potential effects of sound on marine mammals, particle motion is rarely discussed. Except for special circumstances (e.g., plane and spherical waves), there is no simple relationship between pressure and particle velocity. The vast majority of studies of hearing in captive marine mammals have been conducted in relatively small enclosed volumes of water, making the plane wave assumption (and *a priori* knowledge of the relationship between pressure and velocity) invalid.

It is important to distinguish between the *source level* (SL), or level measured 1 m from the source, vs the *received level* (RL), which is the level measured at the receiver (usually a marine mammal herein).

The term "intensity" is often used generally with respect to subjective acoustic parameters (i.e., loudness), but it is used here in a strict sense. Sound intensity is normally defined as the time-averaged active intensity (Kinsler et al., 1982; Fahy, 1995); this quantity corresponds to local net transport of sound energy and is related to the product of the sound pressure and the particle velocity component in-phase with the sound pressure. In the majority of laboratory studies, complex sound fields typically create complex, spatially varying relationships between pressure and velocity. In these circumstances, sound intensity cannot be estimated from pressure measurements alone (which assume that pressure and particle velocity are in-phase), and specific measurements of the sound particle velocity (or pressure gradient) are required in order to characterize intensity.

We distinguished two basic sound types: (1) *pulse* and (2) *nonpulse*. Our operational definitions of sound types are given in Chapter 2, "Structure of the Noise Exposure Criteria," and are discussed at greater length in Appendix A. The pulse/nonpulse distinction is important because pulses generally have a different potential to cause physical effects, particularly on hearing (e.g., Ward, 1997).

Peak sound pressure (P_{max}) is the maximum absolute value of the instantaneous sound pressure during a specified time interval and is denoted in units of Pascals (Pa). It is in no sense an averaged pressure. Peak pressure is a useful metric for either pulse or nonpulse sounds, but it is particularly important for characterizing pulses (ANSI, 1986; Harris, 1998, Chapter 12). Peak-to-peak sound pressure is the algebraic difference between the maximum positive and maximum negative instantaneous peak pressure. The mean-squared pressure is the average of the squared pressure over some duration. Sound pressure levels are given as the decibel (dB) measures of the pressure metrics defined above. The RMS SPL is given as dB re: 1 µPa for underwater sound and dB re: 20 µPa for aerial sound. Peak sound pressure levels are denoted hereafter as dB re: 1 µPa (peak) in water and dB re: 20 µPa (peak) in air. Peak-to-peak sound pressure levels are dB re: 1 µPa (peak-to-peak) in water and dB re: 20 µPa (peak-to-peak) in air.

Duration is the length of a sound in seconds. Duration is important because it affects other sound measures, specifically mean-square and/or RMS sound pressure (Madsen, 2005). Because of background noise and reverberation, duration can be difficult to specify precisely, but a functional definition (see Appendix A) is used here.

Sound exposure level (SEL) is a measure of energy. Specifically, it is the dB level of the time integral of the squared-instantaneous sound pressure normalized to a 1-s period. It can be an extremely useful metric for assessing cumulative exposure because it enables sounds of differing duration, sometimes involving multiple exposures, to be compared in terms of total energy. Several methods exist for summing energy over multiple exposures to generate a single exposure "equivalent" value. The relatively straightforward approach used here is described in Appendix A (eq. 5). This summation procedure essentially generates a single exposure "equivalent" value that assumes no recovery of hearing between repeated exposures. As discussed below, recovery functions for marine mammal TTS during and following multiple exposures are still unknown; however, considering nominal TTS recovery functions in terrestrial mammals when exposures occur minutes to hours apart (see Kryter, 1994; Ward, 1997), the above summation procedure would likely overestimate the effect of multiple exposures in many conditions. This summation procedure was intentionally selected as a precautionary measure in the absence of empirical information, although note the temporal conditions given in the "Sound Types" section of Chapter 2. The appropriate units are dB re: 1 μPa^2-s for underwater SEL and dB re: $(20\ \mu Pa)^2$-s for aerial SEL.

Frequency-selective weighting is often employed to measure (as a single number) sound pressure or energy in a specific frequency band of sound, with emphasis or de-emphasis on particular frequencies as a function of the relative sensitivity of a receiver. For aerial hearing in humans, A-weighting is derived from the inverse of the idealized 40-phon equal loudness hearing function across frequencies, standardized to 0 dB at 1 kHz (Harris, 1998). This provides level measures denoted as dB(A). C-weighting is determined from the inverse of the idealized 100-phon equal loudness hearing function (which differs in several regards from the 40-phon function), standardized to 0 dB at 1 kHz (Harris, 1998). This provides level measures denoted as dB(C). In the absence of equal-loudness contours for marine mammals, special frequency-weighting functions based loosely on human C-weighting and general knowledge of functional hearing bandwidth were developed here for functional marine mammal hearing groups (see the "Marine Mammal Functional Hearing Groups" section of Chapter 2).

Other measures of noise interference with critical functions in humans, including the Articulation Index (French & Steinberg, 1947) and the more recent Speech Interference Level (see Beranek & Ver, 1992), focused on the perception of speech and effects of noise. Consequently, exposure criteria geared toward speech perception (e.g., Beranek, 1989) focus on a frequency bandwidth narrower than the audible bandwidth. For a detailed discussion of speech intelligibility and noise impacts, see Chapter 6 in Kryter (1994). It is clear that the perception of conspecific vocal signals in marine mammals is critically important in various life history functions (discussed below; see Wartzok & Ketten, 1999) and that interference with these functions may have particularly negative consequences.

The hypothesis that vocalizations coincide with the range of hearing is based on an adaptive argument that vocal energy should be selected to lie within the range of hearing for maximum efficiency of communication. However, several lines of evidence suggest that other adaptive pressures may shape the vocal range. First, vocal anatomy may produce energy at other frequencies as a byproduct of producing sound within the hearing range. If there is no pressure to eliminate these frequencies, they can be expected to persist. An example is the ultrasonic components of hummingbird song, which lie well outside the range of bird hearing (Pytte et al., 2004). Second, to promote long-range transmission, the vocal range may be adapted to produce greater energy at the low end of the range than would be expected based on the auditory threshold function (Larom et al., 1997). Greater relative energy at low frequencies is also seen in a number of primate species as a byproduct of producing the formant structure of their calls (Fitch & Hauser, 1995). Finally, animals may produce sounds with disproportionate low-frequency information to signal greater size, potentially targeting predators rather than conspecifics (Fitch, 1999; Matrosova et al., 2007). Thus, a number of selective forces can drive the development of an emphasis on low-frequency energy in vocalizations not matched by the shape of the auditory threshold function. While vocal range can be expected to correlate with hearing range to some degree, giving a rough indication of the frequency range of hearing, it cannot be used to estimate either the shape of the auditory threshold function or to assign upper and lower frequency limits.

We lack sufficient empirical data on whether vocal frequency range sufficiently predicts all frequencies that are biologically significant, however.

Certain marine mammal responses to anthropogenic sounds, such as the sometimes strong reactions by beaked whales to mid-frequency sonar, would not be expected if only sounds within the bandwidth of vocal output were important in predicting a behavioral response. Hence, our precautionary frequency-weighting approach assumes that the full audible band is relevant. As additional data become available on both hearing capabilities (specifically, equal-loudness contours) and behavioral responses to natural (including conspecific) and anthropogenic sounds, a more refined means of frequency-weighting than the intentionally precautionary (broad) M-weighting functions may be recommended.

Kurtosis is a statistical measure of a probability distribution often applied to describe the shape of the amplitude distribution (Hamernik & Hsueh, 1991; Lei et al., 1994; Hamernik et al., 2003). In some regards, it appears to be a highly relevant metric in that impulsive sound with high negative kurtosis, rapid onset, and high instantaneous peak-pressure may be particularly injurious to some mammals (Hamernik et al., 2003).

Sound Production and Use in Marine Mammals

As a general statement, all studied marine mammals can produce sounds in various important contexts. They use sound in social interactions as well as to forage, to orient, and to respond to predators. Interference with these functions, through the various effects of noise on hearing and/or behavior identified below, thus has the potential to interfere with vital rates identified by the NRC (2005) as particularly significant effects of exposure.

The noise exposure criteria given here are focused on current knowledge of hearing and the effects of noise on hearing and/or behavior in marine mammals. Thus, a detailed discussion and review of the expansive literature on the production and the uses of sound is beyond the scope of this paper; interested readers are referred to the many reviews of marine mammal acoustic signals (e.g., Schusterman, 1981; Watkins & Wartzok, 1985; Au, 1993; Richardson et al., 1995; Wartzok & Ketten, 1999; Clark & Ellison, 2004). Because of the extreme importance of detecting conspecific social signals in marine mammal life history functions, however, a brief and very general discussion of sound output characteristics in the major marine mammal groups is given here.

The large whales (mysticete cetaceans, as described below) generally produce low-frequency sounds in the tens of Hz to the several kHz band, with a few signals extending above 10 kHz. These sounds appear to serve predominantly social functions, including reproduction and maintaining contact, but they may also play some role in spatial orientation.

The dolphins and porpoises (odontocete cetaceans, also described below) produce sounds across some of the widest frequency bands that have been observed in animals. Their social sounds are generally in the range audible to humans, from a few hundreds of Hz to several tens of kHz, but specialized clicks used in biosonar (echolocation) systems for prey detection and navigation extend well above 100 kHz.

Pinnipeds (seals, sea lions, and walruses) also produce a diversity of sounds, though generally over a lower and more restricted bandwidth (generally from 100 Hz to several tens of kHz). Their sounds are used primarily in critical social and reproductive interactions. Pinnipeds spend time both at sea and on land, however, and thus produce sounds in both water and air.

Because sound production in marine mammals is integral to so many important behaviors, interference with these communicative functions is considered to be particularly adverse (see severity scaling described in Chapter 4, "Criteria for Behavioral Disturbance"). As discussed in Chapter 5, considerable additional research is needed to identify conditions in which anthropogenic noise exposure interferes with acoustic communication as well as ways in which marine mammals cope with masking noise to overcome interference in detecting real-world signals in complex, 3-dimensional marine environments.

Responses to Sound

Animals exposed to either natural or anthropogenic sound may experience physical and psychological effects, ranging in magnitude from none to severe. This brief discussion considers the range of potential impacts, which depend on spatial relationships between a sound source and the animal receiver; sensitivity of the receiver; received exposure level, duration, and duty cycle; and many other factors (see also Richardson et al., 1995).

The same acoustic source may have radically different effects depending on operational and environmental variables, and on the physiological, sensory, and psychological characteristics of exposed animals. It is important to note that these animal variables may differ (greatly in some cases) among individuals of a species and even within individuals depending on various factors (e.g., sex, age, previous history of exposure, season, and animal activity). Responses elicited can depend both on the context (feeding, mating, migrating, etc.) in which an individual is ensonified and on a host of experiential variables (see Wartzok et al., 2004). Consequently, certain effects may be poorly described with simple measures such as SPL alone, and may only be predictable when additional variables are considered. We considered all known factors in developing the noise exposure criteria proposed here, but data limitations precluded the derivation of explicit exposure criteria for all of the effects discussed below.

Audibility

When a sound can be perceived amidst background noise, it is considered to be audible. Audibility can differ from detectability in that a receiving system may detect a signal at some level even when it is incapable of meaningful perception. Audibility is determined by the characteristics of received sound, characteristics of the receiving system, and background noise conditions (either external or internal). Audition (hearing) is a well-developed and primary sensory modality for most, if not all, marine vertebrates (Schusterman, 1981; Tyack, 1998; Fay & Popper, 2000). It involves coding, processing, integrating, and responding to sound in a variety of ways, some not outwardly evident (Yost, 2000). Like other animals, marine mammals have multiple sound-reception pathways and rely on signal processing at multiple levels integrated within the cochlea and nervous system to optimize perception.

Marine mammal hearing capabilities are quantified in live subjects using behavioral audiometry and/or electrophysiological techniques (e.g., Schusterman, 1981; Au, 1993; Kastak & Schusterman, 1998; Wartzok & Ketten, 1999; Nachtigall et al., 2000, 2007; Finneran & Houser, 2006; André & Nachtigall, 2007; Supin & Popov, 2007). For species not studied with *in vivo* audiometry, some auditory characteristics can be estimated based on sound production frequencies; on observations of sound characteristics that either do or do not elicit behavioral responses in untrained animals (e.g., Richardson et al., 1995; Erbe, 2002); or on auditory morphology, including biomechanical properties of the basilar membrane and other characteristics (Wartzok & Ketten, 1999).

Behavioral audiograms are obtained from captive, trained animals using standard psychometric testing procedures. With appropriate controls and sufficient training, behavioral data are presently considered to most accurately represent hearing capabilities of a test subject. Behavioral audiometric studies are time-consuming, however, and the results depend on the training and attention of subjects as well as the background noise conditions in captive settings. Because marine mammals are large and difficult to maintain, behavioral audiograms representing an entire species are typically based on a few individuals (often one animal). Additionally, subjects are generally obtained opportunistically (e.g., individuals rehabilitated after stranding) rather than by random sampling of individuals from wild populations. This may provide a somewhat biased representation of "normal" hearing for the species if rehabilitated animals have compromised hearing capabilities (see André et al., 2007). Individual differences in hearing sensitivity among subjects, and methodological differences among investigators, can lead to improper conclusions when nominal species audiograms are based on data from a single animal (e.g., compare Hall & Johnson, 1972, with Szymanski et al., 1999). Hearing sensitivity has been measured using behavioral methods in fewer than 20 of the ~128 cetacean and pinniped species (based on the taxonomy of Rice, 1998).

Electrophysiological audiometry involves measuring small electrical voltages (auditory evoked potentials [AEPs]) produced by neural activity when the auditory system is stimulated by sound. With this technique, neural responses are typically averaged while many relatively short duration signals are presented. This technique is comparatively fast and less sensitive to factors such as subject experience and reproductive, behavioral, or motivational states that affect behavioral audiometry. Whereas behavioral audiograms can only be made with trained, captive animals, AEP measures of sound detection can also be made with untrained individuals that are stranded, temporarily restrained, or in rehabilitation (see Cook et al., 2006; André et al., 2007; Delory et al., 2007; Taylor et al., 2007).

AEP and behavioral techniques measure different features of the auditory system and may generate somewhat different measured results. Relevant comparisons of AEP and behavioral audiograms are limited and are the subject of ongoing scientific investigation. Besides the need to obtain both types of data on the same individuals, there are complications due to differences in the types of test stimuli used by different researchers, problems in estimating the true RL at the relevant sensory organ(s), and the difficulty of determining absolute signal amplitudes that barely elicit neural responses. Even so, Yuen et al. (2005), Finneran et al. (2007b), and Schlundt et al. (2007) demonstrated that, with carefully calibrated and repeated measurements, the two procedures can produce comparable detection thresholds in at least a few cetacean species.

An auditory threshold, estimated by either behavioral or electrophysiological responses, is the level of the quietest sound audible in a specified percent of trials. An auditory threshold is not an invariant critical value above which a sound is always heard and below which it is never heard. Instead, it is a sound level at which there is an explicit signal detection probability (often 50%; determined *a priori*). This probability depends on a number of intrinsic factors (Green & Swets, 1974; Egan, 1975; McMillan & Creelman, 1991). In all species tested thus far, the hearing response in relation to frequency is a generally U-shaped curve with a frequency range of best sensitivity (lowest hearing thresholds) and frequencies both below and above this range where sensitivity is relatively poor (higher threshold values). Species differ in absolute sensitivity and functional frequency bandwidth (see Fay, 1988; Richardson et al., 1995), such that identical sounds may be perceived radically differently by individuals of different species. Individual differences within species have also been demonstrated in some terrestrial species (see Fay, 1988) and, to a lesser extent, in marine mammals as well (see Houser & Finneran, 2006b, for the most definitive example of this). Sounds whose levels barely exceed background noise levels may be detectable but may or may not elicit changes in individual behavior. Ideally, "absolute" or unmasked hearing thresholds should be measured in low background noise conditions such as anechoic testing enclosures. While this is standard practice in human audiometry, very few of the marine mammal hearing data obtained to date have been measured in such conditions. Limited recent data obtained with pinnipeds tested in a hemi-anechoic testing chamber in air (described in Kastak et al., 2005) suggest that masking from environmental noise in testing enclosures may have significantly affected measurements of "absolute" hearing; thresholds in a harbor seal (*Phoca vitulina*) were in fact ≥ 30 dB lower in very low background noise conditions (Holt et al., 2001).

While the above concepts and studies are essential in understanding general hearing capabilities (e.g., functional bandwidth, range of best hearing sensitivity) of marine mammals, animals in the "real world" rarely listen for simple acoustic signals from point sources and do not live in a noise-controlled environment. Rather, they are presented with spatially complex and time-varying streams of acoustic information in often noisy environments. Measurements using simple sound stimuli have indicated that marine mammals are generally quite adept at localizing acoustic sources in laboratory conditions (Møhl, 1964; Gentry, 1967; Terhune, 1974; Moore & Au, 1975; Renaud & Popper, 1975; Holt et al., 2004, 2005). Many of the behavioral observations discussed in Chapter 4 (and in Appendices B & C) indicated relatively precise orientation behaviors to sound sources (or sound localization) in the field as well. Limited laboratory data are also available regarding how marine mammals detect relatively simple stimuli over background masking noise (discussed below). A more complex perceptual matter related to localization and detection over masking noise is the manner in which vertebrates process complex information to perceive the acoustic (or auditory) scene—that is, gain useful information from the suite of sounds around them in the real world (e.g., Fay & Popper, 2000).

Bregman (1990) considered how the human auditory system constructs a perceptual acoustic image of the surrounding environment and events occurring in that environment. He posits that, as in visual perception, hearing systems are organized in such a manner that related acoustic events (such as the frequency structure of a harmonic signal or a repeated signal from the same source in a 3-dimensional space) are grouped perceptually in a meaningful way. According to the process of *auditory scene analysis*, the auditory system sorts-out related elements of a complex natural acoustic environment into those arising from different sound sources. Furthermore, previous experience can have powerful effects on the processing and interpretation of sounds. This too is similar to psychological processes underlying visual perception in which the range to an object may be inferred from knowledge of an object's general size and physical appearance.

Presuming such capabilities occur in marine vertebrates, which is logical given the importance of sound to marine mammals, it seems likely that they could perceive range and the general nature (e.g., movement) of sound sources. *Acoustic stream segregation*, the identification of relatively simple stimuli from different, overlapping patterns, has been demonstrated in several bird and bat species (MacDougall-Shackleton et al., 1998; Moss & Surlykke, 2001). Neither acoustic stream segregation nor auditory scene analysis has yet been investigated in marine mammals (but see Madsen et al., 2005a). Each of these processes, along with more data on sound localization, may be relevant in the continued development of appropriate marine mammal noise exposure criteria (see the "Marine Mammal Functional Hearing Groups" section of Chapter 5, for research recommendations).

Auditory Masking

Noise may partially or entirely reduce the audibility of signals, a process known as *auditory masking*. The extent of interference depends on the spectral, temporal, and spatial relationships between signals and masking noise, in addition to other factors. Human auditory systems perform frequency-based assessment (similar to Fourier analysis) on incoming signals such that, for most exposure levels, significant masking of tonal signals is almost exclusively by noise in a narrow band (called the critical band) of similar frequencies (Wegel & Lane, 1924; Fletcher, 1940; Greenwood, 1961). With increasing masker level, however, there is an asymmetrical spread in the masking effect such that detection of frequencies above those of the masking stimulus is more significantly impeded (see Buus, 1997; Yost, 2000).

Because of common biomechanical cochlear properties across taxa (Echteler et al., 1994), masking is expected to follow similar principles in other mammals (including marine mammals). The structure and function of the outer and middle ear differ profoundly between terrestrial and marine mammals (Wartzok & Ketten, 1999); however, the characteristics of auditory masking are strikingly similar among nonspecialized mammals in general (Fay, 1988; Echteler et al., 1994), including marine mammals tested in air and in water (Turnbull & Terhune, 1990; Southall et al., 2000, 2003). Similarities in morphology and mammalian cochlear functional dynamics (as revealed by masking studies) suggest that auditory data from terrestrial mammals may be reliably used in some situations where marine mammal data are lacking. Data on auditory masking in marine mammals are not presented in detail here because they are not directly used in formulating the recommended noise exposure criteria (but see Southall et al., 2000, 2003, for reviews).

Auditory Threshold Shift

Animals exposed to sufficiently intense sound exhibit an increased hearing threshold (i.e., poorer sensitivity) for some period of time following exposure; this is called a *noise-induced threshold shift* (TS). Factors that influence the amount of TS include the amplitude, duration, frequency content, temporal pattern, and energy distribution of noise exposure. The magnitude of TS normally decreases over time following cessation of the noise exposure. The amount of TS just after exposure is called the initial TS.

If TS eventually returns to zero (i.e., the threshold returns to the pre-exposure value), it is called TTS. The following physiological mechanisms are thought to play some role in inducing TTS, also referred to as auditory fatigue: effects on sensory hair cells in the inner ear that reduce their sensitivity, modification of the chemical environment within sensory cells, residual middle-ear muscular activity, displacement of certain inner ear membranes, increased blood flow, and post-stimulatory reduction in both efferent and sensory neural output (Kryter, 1994; Ward, 1997). Where these effects result in TTS rather than a permanent change in hearing sensitivity, they are within the nominal bounds of physiological variability and tolerance and do not represent physical injury (Ward, 1997). Recovery of nominal hearing function may occur quickly, and the amount of TTS measured depends on the time elapsed since the cessation of noise exposure; subscripts are used to indicate the time in minutes after exposure. For example, TTS_2 means TTS measured 2 min after exposure cessation.

If TS does not return to zero after a relatively long interval (on the order of weeks), the residual TS is called a noise-induced permanent threshold shift (PTS). The distinction between PTS and TTS depends on whether there is a complete recovery of TS following noise exposure. PTS is considered to be auditory injury. Some of the apparent causes of PTS in mammals are severe extensions of effects underlying TTS (e.g., irreparable damage to the sensory hair cells). Others involve different mechanisms, such as exceeding the elastic limits of certain tissues and membranes in the middle and inner ears and resultant changes in the chemical composition of inner ear fluids (Ward, 1997; Yost, 2000). The relationship between TTS and PTS depends on a highly complex suite of variables concerning the study subject and the exposure. This relationship remains poorly understood, even for humans and small terrestrial mammals in which this topic has been investigated intensively (see Kryter, 1994; Yost, 2000).

In addition to the potential for discrete, intense sounds to result in TTS or PTS, chronic sound exposure, common in industrialized societies, can result in noise-induced PTS in humans as they age (see Kryter, 1994). Reduced hearing sensitivity as a simple function of development and aging (*presbycusis*) has been demonstrated in both children (Roche et al., 1978) and adults (e.g., Brant & Fozard, 1990). In the long-term, noise-induced hearing loss and presbycusis appear to result in a progressive PTS that is a complex, nonlinear process and particularly affects high-frequency hearing. Limited research in cetaceans and pinnipeds has revealed patterns of presbycusis that are similar to those observed in humans (Ridgway & Carder, 1997; Brill et al., 2001; Schusterman et al., 2002; Houser & Finneran, 2006b; Reichmuth et al., 2007), further underscoring certain general similarities in auditory processes across mammals.

PTS and TTS data from humans and nonhuman terrestrial mammals were used to develop safe exposure guidelines for human work environments (e.g., NIOSH, 1998). For marine mammals, recent data are available regarding sounds that cause modest TTS (generally < 20 dB decrease in sensitivity) in a few species of odontocetes and pinnipeds. No data exist on exposures that would cause PTS in these taxa, however (see Chapter 2 for detailed discussions). Consequently, the only current option for estimating exposure conditions that would cause PTS-onset in marine mammals is to use the available marine mammal TTS data combined with data from terrestrial mammals on TTS growth rates with increasing acoustic exposure (see the "Criteria for Injury: TTS and PTS" section of Chapter 3).

Behavioral Reactions to Sound

Behavioral responses to sound are highly variable and context-specific (see Wartzok et al., 2004, for a discussion). Some sounds that are audible to animals may elicit no overt behavioral response. This is most common when the sound does not greatly exceed the minimum detectable level and is not increasing or fluctuating (Richardson et al., 1995). Inability to detect an overt response does not necessarily mean that there is no subtle behavioral (or other) effect, however.

When observable reactions do occur, they may include orientation or attraction to a sound source; increased alertness; modification of characteristics of their own sounds; cessation of feeding or social interaction; alteration of movement/diving behavior; temporary or permanent habitat abandonment; and, in severe cases, panic, flight, stampede, or stranding, sometimes resulting in injury or death (e.g., Richardson et al., 1995; Evans & England, 2001; Gordon et al., 2004; Scheifele et al., 2005; Cox et al., 2006; Nowacek et al., 2007). Minor or temporary behavioral effects are often simply evidence that an animal has heard a sound and may not indicate lasting consequence for exposed individuals. For the purposes of setting criteria, the effects of greatest concern are those that may negatively impact reproduction or survival. Ultimately, it is the biological relevance of the reaction in terms of vital parameters that must be determined. In proposing noise exposure criteria, one must clearly and explicitly differentiate trivial effects from those with the potential to affect vital rates. However, it has proven to be exceedingly challenging to distinguish among and rank the various effects and to establish a generally accepted definition of biologically meaningful behavioral disturbance (see NRC, 2005).

Except for naïve individuals, behavioral responses depend critically on the principles of *habituation* and *sensitization*. An animal's exposure history with a particular sound affects whether it is subsequently less likely (habituation) or more likely (sensitization) to respond to a stimulus such as sound exposure. The processes of habituation and sensitization do not necessarily require an association with a particular adverse or benign outcome. Rather, individuals may be innately predisposed to respond to certain stimuli in certain ways. These responses may interact with the processes of habituation and sensitization for subsequent exposure. Where associative learning occurs, individuals link a particular exposure with a known outcome (positive, negative, or neutral) and use that information in guiding future decisions on whether and how to respond to similar stimuli. The relationship between these two categories of learning (non-associative and associative) can be highly complex, particularly for experienced individuals (see Deecke et al., 2002).

Many contextual variables may be powerful contributors to an animal's perception of and reaction to the acoustic scene. These include the perception of source proximity (nearness), relative movement (encroachment or retreat), and general novelty or familiarity, all of which may affect the type and magnitude of the resulting behavioral response(s). In terms of proximity, the presence of high-frequency components in a sound and the lack of reverberation, both of which are indicative of proximity, may be more relevant acoustic cues of spatial relationship than simply exposure level alone (see P. Miller, 2002). If a source is perceived to be approaching, the response is often stronger. In addition, the activity of the individual and its fidelity to a current location often affect the response.

Thus, in addition to source characteristics, other factors that may be critical in determining behavioral effects include past experience, situational variables, receiver auditory systems, and the extent to which the sound resembles familiar benign or noxious stimuli (e.g., Irvine et al., 1981; NRC, 2005). Animals that fail to exhibit general avoidance when exposed to a certain sound source may still detect the sound but are either habituated to exposure or may display less dramatic behavioral responses (e.g., altering vocal behavior, modifying orientation/movement patterns).

The magnitude of a given behavioral response may not be a direct function of exposure levels or even of the animal's experiential history. If the sound triggers an anti-predator response in the subject (e.g., Irvine et al., 1981; Finley et al., 1990), the response magnitude may reflect the individual's underlying physiological condition, the relative costs in fitness of failing to respond, the availability of alternative refuges, and other factors specific to predator defense (Gill & Sutherland, 2000; Frid & Dill, 2002; Beale & Monaghan, 2004).

For all these reasons, behavioral responses to anthropogenic sounds are highly variable. Meaningful interpretation of behavioral response data (and biologically relevant conservation decisions) must consider not only the relative magnitude and apparent severity of behavioral reactions to human disturbance but also the relevant acoustic, contextual, and ecological variables. In many cases, specific acoustic features of the sound and contextual variables (e.g., proximity, subject experience and motivation, duration, or recurrence of exposure) may be of considerably greater relevance to the behavioral response than simple acoustic variables such as exposure RL. For example, if an anthropogenic sound is perceived as indicating the presence of a predator, it is likely to trigger a strong defensive reaction at relatively low RLs. On the other hand, sounds that resemble conspecific signals may be ignored or induce approach or avoidance, depending upon the context. Further, typically neutral sounds may cause increasing annoyance reactions (such as avoidance) as a function of exposure level. This makes it difficult or impossible to justify basing broad, objective determinations of impact thresholds on RL alone. This is the primary reason why this paper does not propose explicit behavioral disturbance criteria levels for certain sound types. Rather, we collated available data relating acoustic exposure to the severity of observed behavioral response in a form that allows a variety of relationships to be estimated (Chapter 4). When research allows the separation of annoyance from cases where an animal interprets sounds as signals from predators, prey, or conspecifics, it may become possible to classify signals and predict responses more precisely.

Non-Auditory Effects

The auditory system appears to include the organs most susceptible to noise exposure, at least in humans (e.g., Ward, 1997). The limited data on captive marine mammals exposed to various kinds of noise support a similar conclusion, suggesting that TTS-onset occurs at levels which may be below those required for direct non-auditory physiological trauma (but see discussion of deep-diving species below). Noise exposure does have the potential to induce a range of direct or indirect physiological effects on non-auditory structures. These may interact with or cause certain behavioral or auditory effects, or they may occur entirely in the absence of those effects.

Noise exposure may affect the vestibular and neurosensory systems. For instance, in humans, dizziness and vertigo can result from exposure to high levels of noise, a condition known as *nystagmus* (see Oosterveld et al., 1982; Ward, 1997; Halmagyi et al., 2005). Little is known about vestibular functions in marine mammals. There are significant differences in vestibular structures in some marine mammal species compared to most land mammals (Wartzok & Ketten, 1998; Ketten, 2000). In cetaceans in particular, the vestibular components are sufficiently reduced and have such low neural representation that the principal function may be essentially to provide limited gravitational and linear acceleration cues. Pinnipeds by contrast have a well-developed, more conventional vestibular apparatus that likely provides multiple sensory cues similar to those of most land mammals. Both pinnipeds and cetaceans retain the direct coupling through the vestibule of the vestibular and auditory systems; therefore, it is possible, albeit not known, that marine mammals may be subject to noise-induced effects on vestibular function as has been shown in land mammals and humans. Responses to underwater sound exposures in human divers and other immersed land mammals suggest that vestibular effects are produced from intense underwater sound at some lower frequencies (Steevens et al., 1997). Theoretical effects on the human vestibular system as well as other organs (e.g., lungs) from underwater sound exposures also have been explored through models (Cudahy & Ellison, 2002); however, there are no comparable measurements or models for marine mammals at this point from which to estimate such effects. Data are clearly needed for all major marine mammal taxa to more fully assess potential impacts on non-auditory systems.

Relatively low-level physiological responses include changes in cardiac rate (*bradycardia* or *tachycardia*) and respiratory patterns, which may lead to changes in metabolism. Stress reactions in humans and other vertebrates include various physiological changes to pulmonary, cardiac, metabolic, neuro-endocrine, immune, and reproductive functions (e.g., Hales, 1973; Lee, 1992; Vrijkotte et al., 2000). Studies of noise-induced stress in marine mammals are very limited, but endocrine secretions of glucocorticoids and altered cardiovascular function have been documented in odontocetes exposed to high-level sound (Romano et al., 2004; *cf.* Thomas et al., 1990c). Noise exposure also often leads to changes in surfacing-respiration-dive cycles of cetaceans (e.g., Richardson & Malme, 1993), which may have various physiological effects. Assuming that effects in marine and terrestrial mammals are similar, intermediate physiological responses to stressors (including noise) may accompany avoidance or aggressive behaviors and include single auditory startle responses, the initiation and sustenance of the catecholamine response, and physiological preparation for fight or flight. The most severe physiological responses would include multiple or repeated auditory startle responses, triggering of the hypothalamic-pituitary-adrenal (HPA) axis and associated elevated blood glucocorticoid level, substantially altered metabolism or energy reserves, lowered immune response, diminished reproductive effort, and potential tissue trauma (e.g., Sapolsky et al., 2000). [The issue of stress responses to noise exposure has been discussed recently by Wright et al. (in press).]

Sound at certain frequencies can cause an air-filled space to vibrate at its resonant frequency (acoustic resonance), which may increase the likelihood of mechanical trauma in the adjacent or surrounding tissue. The resonant frequencies of most marine mammal lungs are below the operating frequencies of many anthropogenic sound sources (Finneran, 2003). Further, biological tissues are heavily damped, estimated tissue displacement at resonant frequencies is predicted to be exceedingly small, and lung tissue damage is generally uncommon in acoustic-related marine mammal stranding events. For these reasons, specialists do not regard lung resonance as a likely significant non-auditory effect for marine mammals exposed to anthropogenic noise sources that operate above 100 Hz (U.S. Department of Commerce, 2002). This conclusion might not apply to lower-frequency sources that operate at a particular frequency for a significant duration.

The non-auditory effect now being most actively discussed in marine mammalogy is nitrogen gas bubble growth, resulting in effects similar to decompression sickness in humans. Jepson et al. (2003) and Fernández et al. (2004, 2005) hypothesized that lesions (gas and fat emboli) observed in individual beaked whales found stranded after military sonar exercises were somehow caused by *in vivo* nitrogen bubble formation. Osteonecrosis in sperm whales has further been suggested as a chronic result of nitrogen bubble formation (Moore & Early, 2004).

To date, the gas bubble hypothesis remains untested, and the acoustic causative mechanism for formation of emboli, if any, is unknown. Theoretically, bubble precursors in supersaturated, homogenized tissue may incrementally enlarge during the successive passage of compression and rarefaction portions of acoustic waves that exceed static pressure (rectified diffusion; Crum & Mao, 1996). Alternatively, a single acoustic exposure could activate bubble precursors, allowing them to grow by gradual expansion into bubbles in nitrogen-supersaturated tissue (static diffusion; see Potter, 2004). The diving patterns of some marine mammals increase gas-tissue saturation and potentially could increase the susceptibility of noise-exposed animals to bubble growth via either mechanism (Ridgway & Howard, 1979; Houser et al., 2001b). Nitrogen supersaturation levels for deep-diving species of interest, including beaked whales, are based on theoretical models, however (Houser et al., 2001b). No unequivocal support for either pathway presently exists.

The evidence for bubble formation as a causal mechanism between certain types of acoustic exposure and stranding events remains equivocal. At a minimum, scientific disagreement and/or complete lack of information exists regarding the following important points: (1) received acoustic exposure conditions for animals involved in stranding events; (2) pathological interpretation of observed lesions in stranded marine mammals (Fernández et al., 2004; Piantadosi & Thalmann, 2004); (3) acoustic exposure conditions required to induce such physiological trauma directly; (4) whether noise exposure may cause behavioral reactions (e.g., atypical diving behavior) that secondarily induce bubble formation and tissue damage (Jepson et al., 2003; Fernández et al., 2005; Zimmer & Tyack, 2007); and (5) the extent that *post mortem* artifacts introduced by decomposition before sampling, handling, freezing, or necropsy procedures affect interpretation of observed lesions. Tests of the gas bubble hypothesis may yield data pertinent to future marine mammal noise exposure criteria, but too little is currently known to establish explicit exposure criteria for this proposed mechanism.

Courtesy: A. Friedlander

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2. Structure of the Noise Exposure Criteria

When *de facto* noise exposure guidelines are used by management agencies, they generally are based on a small number of categories of marine mammals and sound types. Though it would be convenient to have a single exposure criterion for all species and sound sources, such a simplified approach is not supported by available science. However, some categorization of species and sources is warranted based on current information. The many anthropogenic sound sources used in marine environments can be categorized based on certain acoustic and operational features. Similarly, there is great diversity in hearing and in the biological effects of noise among marine mammals, but current knowledge supports some functional and/or phylogenetic groupings.

It is also neither possible nor desirable to derive distinct exposure criteria for every species and sound source. Important generalizations across taxa would be missed even if resources and time were adequate to study each species and exposure condition. Further, it is impractical to apply numerous, species-specific criteria when predicting and/or attempting to mitigate effects.

A standard scientific approach in such situations is to categorize animals based on functional characteristics and sound sources based on physical similarities, and to summarize the information in a matrix format. We subdivide cetaceans and pinnipeds into five functional hearing categories based on the frequencies they hear. Other methods of categorization are, of course, possible. For instance, Verboom (2002) relied heavily on direct measurements of noise impacts on hearing to quantify the effects of noise exposure on marine mammals. Some of his proposed criteria are comparable with those presented here. The present effort makes broader use of laboratory and field behavioral and audiometric data, additional recent data, and extrapolations from terrestrial mammals not used by Verboom. We divide sound sources into three types according to acoustic characteristics defined at the source. Note that at a distance, a sound may have significantly different features; categorizing sounds based on source characteristics is a precautionary and pragmatic approach (as is described in the next section). The justifications for and assumptions underlying our categorization of functional hearing groups and sound types are described here. The number of subdivisions in future noise exposure criteria will likely increase as more supporting data are acquired.

The format of the recommended marine mammal noise exposure criteria is thus a matrix of 15 "cells" that systematically considers three sound types (see next section) and five functional marine mammal hearing groups (see the "Marine Mammal Functional Hearing Groups" section of this chapter). Within each of those 15 cells, we consider two general acoustic metrics (see the "Exposure Criteria Metrics" section) and two levels of exposure effect ("Levels of Noise Effect: Injury and Behavorial Disturbance" section of this chapter). Sixty possible criteria result (i.e., 3 sound types × 5 marine mammal groups × 2 metrics × 2 impact levels), although fewer than 60 are reported due to data limitations. Whereas sound types are defined by source features, criteria values represent levels received by individual marine mammals.

Sound Types

Three sound types are used: (1) a single pulse, (2) multiple pulses, and (3) nonpulses. The separation between pulses and nonpulses is supported by data on auditory fatigue and acoustic trauma in terrestrial mammals (e.g., Dunn et al., 1991; Hamernik et al., 1993) and is generally consistent with the sound types distinguished for damage risk criteria in humans (e.g., U.S. DoD, 1997; NIOSH, 1998).

Pulses and nonpulses are distinguished by numerous definitions and mathematical distinctions (e.g., Burdic, 1984). The empirical distinction used here is based on a measurement procedure using several temporal weightings. Various exponential time-weighting functions applied in measuring pulse and nonpulse sounds may yield different measured received levels (RLs) (see Harris, 1998). Most sound level meters (SLM) provide options for applying either a "slow" or "fast" time constant (1,000 or 125 ms, respectively) for measuring nonpulses or an impulse time constant (35 ms) appropriate for measuring pulses. For a sound pulse, the slow or fast SLM settings result in lower sound pressure level (SPL) measurements than those obtained using the impulse setting. Each of these time constants is selected based on properties of the human auditory system. These may be at least generally relevant for other mammalian auditory systems, although further empirical data on temporal resolution in marine mammals are needed (see Chapter 5, "Research Recommendations").

Harris (1998) proposed a measurement-based distinction of pulses and nonpulses that is adopted here in defining sound types. Specifically, a ≥ 3-dB difference in measurements between continuous and impulse SLM settings indicates that a sound is a pulse; a < 3-dB difference indicates that a sound is a nonpulse. We note the interim nature of this distinction for underwater signals and the need for an explicit distinction and measurement standard such as exists for aerial signals (ANSI, 1986).

Harris's (1998) definitions assumed use of A-weighting as do most human-oriented definitions of acoustical measurements; however, different frequency-weighting functions should be used for various animal taxa (as discussed below). Leaving that question aside temporarily, it is instructive to compare the impulse equivalent-continuous sound level (L_{IeqT}) for a sound that increases in level with the corresponding equivalent-continuous level (L_{eqT}). Here, L_{IeqT} has an impulse integration time of 35 ms and L_{eqT}, defined as sound exposure divided by T, is expressed as a level. As an example, suppose that a source is examined over a 2-s period (T = 2 s). The highest L_{AIeq2s} ("A" here denotes A-weighting) during this period is 75.2 dB, and the highest L_{ALeq2s} is 65.1 dB. The difference of 10.1 dB is greater than the 3-dB criterion given by Harris (1998); therefore, the sound is considered to be a pulse.

The distinction between pulses and nonpulses is not always clear in practice. For instance, certain signals (e.g., acoustic deterrent and harassment devices) have characteristics of both pulses and nonpulses. Also, certain sound sources (e.g., seismic airguns and pile driving) may produce pulses at the source but, through various propagation effects, may meet the nonpulse definition at greater distances (e.g., Greene & Richardson, 1988). This means that a given sound source might be subject to different exposure criteria, depending on the distance to the receiver and intervening propagation variables. While this is certainly realistic for many real-world exposures, measurements at the animal are often not practical. Changes in sound characteristics with distance generally result in exposures becoming less physiologically damaging with increasing distance because sharp transient peaks become less prominent. Therefore, these criteria use a precautionary approach and classify sound types based on acoustic characteristics at the source. Additional empirical measurements are needed to advance our understanding of sound type classification as a function of source, range, and environmental variables. We emphasize that the use of source parameters to classify sound types does not negate our decision to recommend exposure criterion levels relative to RLs at the animal.

Treating pulses and nonpulses as discrete sound types is justified by data on mammals in general and several cetacean species in particular (Dunn et al., 1991; Hamernik et al., 1993; also see the "Effects of Noise on Hearing in Marine Mammals TTS Data" section in Chapter 3). Mammalian hearing is most readily damaged by transient sounds with rapid rise-time, high peak pressures, and sustained duration relative to rise-time (for humans: Thiery & Meyer-Bisch, 1988; for chinchillas [*Chinchilla lanigera*], Dunn et al., 1991). Consistent with these results, those odontocetes tested thus far have been shown to experience TTS-onset at lower respective exposure levels if the sound is a pulse rather than a nonpulse (Finneran et al., 2002b, 2005a).

Mammals are also apparently at greater risk from rapidly repeated transients and those with high impulse amplitude *kurtosis* (Erdreich, 1986). Hamernik et al. (1993, 2003) argued that the distinction between exposures with relatively high and low "peakedness" is to some extent an oversimplification. Highly variable threshold shifts can result from exposures of variable peakedness but comparable overall levels, depending on a host of factors. Hamernik et al. (1993, 2003) also noted that peak pressure levels sufficient to exceed mechanical limits of the cochlea, and thus more likely to induce acoustic trauma, tend to be more typical of pulses than nonpulses.

The present criteria also categorize sound types based on repetition. For mammals, single and multiple noise exposures at various levels and durations generally differ in their potential to induce auditory fatigue or trauma. This results principally from the temporal interaction between exposure and recovery periods (e.g., Kryter, 1994) and differences in received total acoustic energy. Further, multiple exposures may increase the likelihood of behavioral responses because of increased probability of detection and the (generally) greater biological significance of continued exposure as opposed to a single, transient event (although see discussion of habituation in the "Responses to Sound" section of Chapter 1).

Single exposures are considered here as discrete acoustic events in which received sound levels exceed ambient noise in at least some portion of the frequency band of functional marine mammal hearing once in a 24-h period; multi-path receptions of a single exposure are not considered multiple exposures. Multiple exposures are considered to be acoustic events causing RLs to exceed ambient noise within the functional bandwidth more than once, with an intervening quiet period not exceeding 24 h. If the exposure event is interrupted, even briefly (other than as a result of the animal's own action—e.g., breaching), it is considered a multiple exposure.

Exposures should be categorized as either pulsed or nonpulsed sounds as described above. Single and multiple exposures to either pulse or nonpulse sounds (or both) are possible. Examples of single pulses and single nonpulses are sounds from a single firing of an airgun or a single vessel passage, respectively.

Multiple pulse or multiple nonpulse sounds are more difficult to delineate, given the diversity and complexity of sound sources. A series exclusively consisting of two or more nonpulses would clearly be a multiple nonpulse exposure (e.g., multiple vessel passages). A multiple pulse exposure would similarly be described as a series exclusively containing pulses (e.g., repeated pile strikes) or a combination of pulses and nonpulses (e.g., the combined vessel noise and airgun transmissions of a seismic vessel). One justification for treating combined pulses and nonpulses as pulses is that the proposed exposure criteria for injury are more precautionary (lower) in the case of pulses than for nonpulses. Specific consideration should be given, on a case-by-case basis, as to whether such a distinction would necessarily be the more precautionary. For instance, if a compound exposure included relatively high-level nonpulses as well as relatively low-level pulses, the more appropriate and protective distinction might be to classify it as a nonpulse exposure.

The proposed exposure criteria for injury from single and multiple exposures to both sound types are numerically identical (Chapter 3). This is another precautionary decision, arising from the fact that no marine mammal data were available regarding the effects of inter-exposure interval on recovery from auditory effects (e.g., TTS). A summation procedure is applied to quantify the fatiguing effects of multiple exposures with an equivalent SEL value (Chapter 1; also Appendix A, eq. 5). The SEL metric takes account of the pressure waveform and duration of either single or multiple sound events; it represents cumulative received energy. This approach effectively negates the need for numerically different injury criteria for single and multiple exposures at the expense of neglecting assumed, but as-yet poorly understood recovery phenomena during intervals between exposures. This is a precautionary approach, pending availability of data on acoustic recovery by marine mammals during intervals between exposures.

When considering behavioral responses, single and multiple nonpulse exposures are considered as a single category. Insufficient information exists to assess the use of SEL as a relevant metric in the context of marine mammal behavioral disturbance for anything other than a single pulse exposure. Future noise exposure criteria for behavioral disturbance may distinguish SPL and SEL exposure criteria for additional conditions, but for most sound types (the exception being single pulses), the available data are best assessed in relation to SPL (discussed in detail in Chapter 4). Consequently, the structure of the exposure criteria matrix includes a categorical distinction between single and multiple pulses given that numerical SEL thresholds are recommended for a single pulse, but not for multiple pulses. No such distinction is made for nonpulses where the available data do not (at least currently) support differential behavioral criteria for single vs multiple exposures.

Thus, the current state of scientific knowledge regarding mammalian hearing and various noise impacts supports three distinct sound types as relevant for marine mammal noise exposure criteria: (1) single pulse, (2) multiple pulses, and (3) nonpulses. Examples of sound sources belonging in each of these categories (based on characteristics of the sound emitted at the source) are given in Table 1. A simplistic measurement procedure using source characteristics (the 3-dB distinction based on Harris, 1998, described above) is used here to distinguish a pulse from a nonpulse, while the simple definitions above distinguish single and multiple exposures.

Table 1. Sound types, acoustic characteristics, and selected examples of anthropogenic sound sources; note sound types are based on characteristics measured at the source. In certain conditions, sounds classified as pulses at the source may lack these characteristics for distant receivers.

Sound type	Acoustic characteristics (at source)	Examples
Single pulse	Single acoustic event; > 3-dB difference between received level using impulse vs equivalent continuous time constant	Single explosion; sonic boom; single airgun, watergun, pile strike, or sparker pulse; single ping of certain sonars, depth sounders, and pingers
Multiple pulses	Multiple discrete acoustic events within 24 h; > 3-dB difference between received level using impulse vs equivalent continuous time constant	Serial explosions; sequential airgun, watergun, pile strikes, or sparker pulses; certain active sonar (IMAPS); some depth sounder signals
Nonpulses	Single or multiple discrete acoustic events within 24 h; < 3-dB difference between received level using impulse vs equivalent continuous time constant	Vessel/aircraft passes; drilling; many construction or other industrial operations; certain sonar systems (LFA, tactical mid-frequency); acoustic harassment/deterrent devices; acoustic tomography sources (ATOC); some depth sounder signals

Marine Mammal Functional Hearing Groups

Species of cetaceans and pinnipeds were assigned to one of five functional hearing groups based on behavioral psychophysics, evoked potential audiometry, auditory morphology, and (for pinnipeds) the medium in which they listen. Cetaceans and pinnipeds are broadly separable based on phylogenetic and functional differences (Reynolds & Rommel, 1999). Cetaceans were further subdivided according to differences in their measured or estimated hearing characteristics and not necessarily according to their phylogeny (as in Wartzok & Ketten, 1999). Pinnipeds are considered a single group, but as amphibious mammals, their hearing differs in air and in water (Kastak & Schusterman, 1998); separate criteria were required for each medium. The taxa in each functional hearing group (based on Rice, 1998) are given in Table 2.

Marine Mammal Hearing

All marine mammals evolved from terrestrial, air-adapted ancestors (Domning et al., 1982; Barnes et al., 1985) and, at least in part, retain the nominal mammalian tripartite peripheral auditory system (i.e., external auditory meatus, air-filled middle ear, and spiral-shaped cochlea). Most of the mechanisms of mammalian hearing are also conserved such as the basic lever structure of the ossicles and the tonotopic organization of the hair cells along the inner ear's basilar membrane.

However, marine mammal auditory systems differ in having some adaptations that seem to be related to pressure, hydrodynamics, and sound reception in water (see Wartzok & Ketten, 1999). For instance, the pinna has been reduced or eliminated in most species, owing to hydrodynamic adaptations. Tissue modifications may enable the reduction or elimination of gas spaces in the middle ear of some marine mammals. Consequently, bone conduction, rather than the conventional ossicular chain, may be an additional (or primary) sound transmission path to the cochlea (e.g., Repenning, 1972; Au, 1993). There are important differences in these adaptations within and between marine mammal taxa.

Knowledge of marine mammal hearing varies widely among groups, but for most species it is quite limited compared to knowledge of terrestrial mammal hearing. Because of the sheer size, limited and disproportionate availability in captive

Table 2. Functional marine mammal hearing groups, auditory bandwidth (estimated lower to upper frequency hearing cut-off), genera represented in each group, and group-specific (M) frequency-weightings

Functional hearing group	Estimated auditory bandwidth	Genera represented (Number species/subspecies)	Frequency-weighting network
Low-frequency cetaceans	7 Hz to 22 kHz	*Balaena, Caperea, Eschrichtius, Megaptera, Balaenoptera* (13 species/subspecies)	M_{lf} (lf: low-frequency cetacean)
Mid-frequency cetaceans	150 Hz to 160 kHz	*Steno, Sousa, Sotalia, Tursiops, Stenella, Delphinus, Lagenodelphis, Lagenorhynchus, Lissodelphis, Grampus, Peponocephala, Feresa, Pseudorca, Orcinus, Globicephala, Orcaella, Physeter, Delphinapterus, Monodon, Ziphius, Berardius, Tasmacetus, Hyperoodon, Mesoplodon* (57 species/subspecies)	M_{mf} (mf: mid-frequency cetaceans)
High-frequency cetaceans	200 Hz to 180 kHz	*Phocoena, Neophocaena, Phocoenoides, Platanista, Inia, Kogia, Lipotes, Pontoporia, Cephalorhynchus* (20 species/subspecies)	M_{hf} (hf: high-frequency cetaceans)
Pinnipeds in water	75 Hz to 75 kHz	*Arctocephalus, Callorhinus, Zalophus, Eumetopias, Neophoca, Phocarctos, Otaria, Erignathus, Phoca, Pusa, Halichoerus, Histriophoca, Pagophilus, Cystophora, Monachus, Mirounga, Leptonychotes, Ommatophoca, Lobodon, Hydrurga,* and *Odobenus* (41 species/subspecies)	M_{pw} (pw: pinnipeds in water)
Pinnipeds in air	75 Hz to 30 kHz	Same species as pinnipeds in water (41 species/subspecies)	M_{pa} (pa: pinnipeds in air)

settings, and, for many species and jurisdictions, the protected status of marine mammals, there are limitations in obtaining hearing data for many species. Behavioral or electrophysiological audiograms exist for fewer than 20 marine mammal species (of ~128 species and subspecies; Rice, 1998). By combining these data with comparative anatomy, modeling, and response measured in ear tissues from species that are difficult to study, however, it is possible to describe the frequency sensitivity and critical adaptations for underwater hearing in each of the five functional hearing groups of marine mammals considered here.

Low-frequency cetaceans consist of 13 species and subspecies of mysticete (baleen) whales in five genera (based on Rice, 1998; see Table 2). No direct measurements of hearing exist for these animals, and theories regarding their sensory capabilities are consequently speculative (for a detailed assessment by species using the limited available information, see Erbe, 2002). They are too large to maintain in the laboratory for psychophysical testing. The limited evoked potential measurements on animals of this size have not yet yielded hearing thresholds (Ridgway & Carder, 2001), but technological advances may soon enable evoked potential audiometry on relatively small and/or young mysticetes. In these species, hearing sensitivity has been estimated from behavioral responses (or lack thereof) to sounds at various frequencies, vocalization frequencies they use most, body size, ambient noise levels at the frequencies they use most, and cochlear morphometry (Richardson et al., 1995; Wartzok & Ketten, 1999; Houser et al., 2001a; Erbe, 2002; Clark & Ellison, 2004). Until better information is available regarding the relationship between auditory sensitivity and marine environmental noise, the sensitivity of mysticetes cannot be easily inferred from the acoustic environment.

The combined information strongly suggests that mysticetes are likely most sensitive to sound from perhaps tens of Hz to ~10 kHz. However, recent data indicated that humpback whales (*Megaptera novaeangliae*) produce some signals with harmonics extending above 24 kHz (Au et al., 2006). These harmonics have considerably lower levels than occur at lower frequencies, and their presence does not necessarily indicate they are audible to the whales. Nonetheless, some high-frequency energy is present. [Additionally, some recent anatomical modeling work by Ketten et al. (2007) suggested that some mysticetes may have functional hearing capabilities at frequencies as high as 30 kHz.] While we do not include these recent results at this time, we note their presence and the possibility that the upper frequency limit of the M-weighting function for mysticetes may need to be revisited based on emerging knowledge. At present, we estimate the lower and upper frequencies for functional hearing in mysticetes, collectively, to be 7 Hz and 22 kHz (Ketten et al., 2007).

Mid- and high-frequency cetaceans are all odontocetes (toothed whales). Unlike the mysticetes, all odontocete cetaceans appear to have highly advanced echolocation (biosonar) systems that use intermediate to very high frequencies (tens of kHz to 100+ kHz: see Au, 1993; Richardson et al., 1995; Wartzok & Ketten, 1999). They also produce social sounds in a lower-frequency band, including generally low to intermediate frequencies (1 kHz to tens of kHz). Consequently, their functional hearing would be expected to cover a wider absolute frequency range than is assumed for mysticetes or has been demonstrated for pinnipeds (discussed below). This has been experimentally confirmed in the odontocete species whose hearing has been measured (discussed below); however, their best hearing sensitivity typically occurs at or near the frequency where echolocation signals are strongest. Based on the differential characteristics of echolocation signals in two groups of odontocetes (see Au, 1993) and on the hearing data described below, odontocetes were divided into mid- and high-frequency functional groups (as seen generally in Wartzok & Ketten, 1999).

Mid-frequency cetaceans include 32 species and subspecies of "dolphins," six species of larger toothed whales, and 19 species of beaked and bottlenose whales (see Table 2). "Functional" hearing in this group was estimated to occur over a wide range of low to very high frequencies. Based on the combined available data, mid-frequency species are estimated to have lower and upper frequency "limits" of nominal hearing at approximately 150 Hz and 160 kHz, respectively. As for the other hearing groups, there is variability within and among species, intense signals below and above the stated bounds may be weakly detectable, and there is a progressive rather than instantaneous reduction in hearing sensitivity near these limits. Mid-frequency cetaceans generally do not appear well-adapted to detect or to discriminate signals outside this frequency band, however. The scarcity (and variability) of empirical data precludes a finer subdivision of this relatively diverse and large group of marine mammals, though it is acknowledged that some mid-frequency species likely have a narrower functional hearing band than the range given above.

Behavioral hearing data are available for the following mid-frequency cetacean species: bottlenose dolphin (*Tursiops truncatus*: Johnson, 1967; Ljungblad et al., 1982; Finneran et al., 2005a), beluga (*Delphinapterus leucas*: White et al., 1978; Awbrey et al., 1988; Johnson, 1992; Ridgway et al., 2001; Finneran et al., 2005b), killer whale (*Orcinus orca*: Hall & Johnson, 1972; Szymanski et al., 1999), false killer whale (*Pseudorca crassidens*: Thomas et al., 1988, 1990a; Au et al., 1997), Risso's dolphin (*Grampus griseus*: Nachtigall et al., 1995; Au et al., 1997); and Pacific white-sided dolphin (*Lagenorhynchus obliquidens*: Tremel et al., 1998).

Audiograms derived using auditory evoked potential (AEP) methodology (Supin et al., 2001) have been obtained for a number of cetacean species. Specific AEP techniques, which involve measuring electrophysiological responses to sound, include those measuring transient evoked responses, such as the auditory brainstem response (ABR) or mid-latency response, and those measuring steady-state evoked responses such as the envelope following response (EFR) or auditory steady-state response (ASSR). Mid-frequency cetacean species tested include the bottlenose dolphin (Bullock et al., 1968; Seeley et al., 1976; Popov & Supin, 1990; Houser & Finneran, 2006b; Finneran et al., 2007a; Hernandez et al., 2007; Popov et al., 2007), killer whale (Szymanski et al., 1999), beluga (Popov & Supin, 1990; Klishin et al., 2000), common dolphin (*Delphinus delphis*: Popov & Klishin, 1998), Risso's dolphin (Dolphin, 2000; Nachtigall et al., 2005, 2007), tucuxi dolphin (*Sotalia fluviatilis*: Popov & Supin, 1990), striped dolphin (*Stenella coeruleoalba*: Kastelein et al., 2003), Pacific white-sided dolphin (Au et al., 2007), false killer whale (Supin et al., 2003), and Gervais' beaked whale (Cook et al., 2006). Additionally, Yuen et al. (2005) conducted a comparative study of behavioral and AEP thresholds for the false killer whale, and Finneran & Houser (2006), Houser & Finneran (2006a), and Finneran et al. (2007b) have compared behavioral and AEP thresholds in multiple bottlenose dolphins.

The high-frequency cetaceans include eight species and subspecies of true porpoises, six species and subspecies of river dolphins plus the franciscana, *Kogia*, and four species of cephalorhynchids (see Table 2). "Functional" hearing in this group was estimated to occur between 200 Hz and 180 kHz. Behavioral audiograms are available for the following high-frequency cetacean species: harbor porpoise (*Phocoena phocoena*: Andersen, 1970; Kastelein et al., 2002a), Chinese river dolphin (*Lipotes vexillifer*: Wang et al., 1992), and Amazon river dolphin (*Inia geoffrensis*: Jacobs & Hall, 1972). Audiograms using AEP methodology have been obtained for three species: harbor porpoise (Popov et al., 1986, 2006; Beedholm & Miller, 2007; Lucke et al., 2007b); finless porpoise (*Neophocaena phocaenoides*: Popov et al., 2006); and Amazon river dolphin (Popov & Supin, 1990).

The pinnipeds include 16 species and subspecies of sea lions and fur seals (otariids), 23 species and subspecies of true seals (phocids), and two subspecies of walrus (odobenids). Pinnipeds produce a wide range of social signals, most occurring at relatively low frequencies. They lack the highly-specialized active biosonar systems of odontocete cetaceans, possibly as a result of their amphibious lifestyle (see Schusterman et al., 2000). Because of this aspect of their life history, pinnipeds communicate acoustically in air and water, have significantly different hearing capabilities in the two media, and may be subject to both aerial and underwater noise exposure (Schusterman, 1981; Kastak & Schusterman, 1998, 1999). These differences necessitate separate noise exposure criteria for pinnipeds in each medium.

For pinnipeds in water, behavioral measures of hearing are available for the northern fur seal (*Callorhinus ursinus*: Moore & Schusterman, 1987; Babushina et al., 1991), California sea lion (*Zalophus californianus*: Schusterman et al., 1972; Moore & Schusterman, 1987; Kastak & Schusterman, 1998, 2002; Southall et al., 2004), northern elephant seal (*Mirounga angustirostris*: Kastak & Schusterman, 1998, 1999; Southall et al., 2004), Hawaiian monk seal (*Monachus schauinslandi*: Thomas et al., 1990b), harp seal (*Pagophilus groenlandicus*: Terhune & Ronald, 1972), ringed seal (*Phoca hispida*: Terhune & Ronald, 1975), harbor seal (Møhl, 1967, 1968; Terhune & Turnbull, 1995; Kastak & Schusterman, 1995, 1998; Southall et al., 2004), and walrus (*Odobenus rosmarus*: Kastelein et al., 2002b). Ridgway & Joyce (1975) measured the gray seal's (*Halichoerus grypus*) underwater hearing using evoked potential audiometry.

For pinnipeds in air, behavioral measures of hearing are available for the northern fur seal (Moore & Schusterman, 1987; Babushina et al., 1991), California sea lion (Schusterman, 1974; Kastak & Schusterman, 1998; Kastak et al., 2004b), northern elephant seal (Kastak & Schusterman, 1998, 1999; Kastak et al., 2004b), harp seal (Terhune & Ronald, 1971), and harbor seal (Møhl, 1968; Kastak & Schusterman, 1998; Kastak et al., 2004b). Aerial hearing in pinnipeds has also been measured using evoked potential audiometry in the gray seal (Ridgway & Joyce, 1975), California sea lion (Bullock et al., 1971; Ridgway & Joyce, 1975; Mulsow & Reichmuth, 2007; Reichmuth et al., 2007), harbor seal (Thorson et al., 1998; Wolski et al., 2003; Mulsow & Reichmuth, 2007; Reichmuth et al., 2007), and northern elephant seal (Houser et al., 2007; Mulsow & Reichmuth, 2007; Reichmuth et al., 2007).

The combined results of these studies indicate that pinnipeds are sensitive to a broader range of sound frequencies in water than in air. The data further suggest differences in the functional hearing range among otariids, phocids, and odobenids, especially under water (Kastak & Schusterman, 1998; Kastelein et al., 2002b). For these proposed noise exposure criteria, however, pinnipeds are considered a single functional hearing group because the data are too limited, both in terms of absolute hearing data and TTS measurements (see "The Effects of Noise on Hearing in Marine Mammals: TTS Data" section in Chapter 3), to support finer subdivisions. We estimate that pinnipeds have "functional" underwater hearing between 75 Hz and 75 kHz and "functional" aerial hearing between 75 Hz and 30 kHz. These ranges are essentially based on data for phocid seals, which have the broadest auditory bandwidths of the pinnipeds. This approach results in a precautionary functional bandwidth for estimating frequency-weighting functions (below) and noise impacts on pinnipeds.

In summary, based on current knowledge of functional hearing in marine mammals, five distinct, functional hearing categories were defined: (1) low-frequency cetaceans (i.e., mysticetes), (2) mid-frequency cetaceans (i.e., most odontocetes), (3) high-frequency cetaceans (i.e., porpoises, river dolphins, pygmy sperm whale, and *Cephalorhynchus*), (4) pinnipeds in water, and (5) pinnipeds in air. The genera in each group, and the estimated lower and upper frequency hearing "limits," are shown in Table 2. Because the five functional hearing groups of marine mammals differ in hearing bandwidth, each may be affected differently by identical noise exposures. Therefore, frequency-weighting functions are required to develop marine mammal noise exposure criteria.

Frequency-Weighting Functions

As a general statement, animals do not hear equally well at all frequencies within their functional hearing range. Frequency weighting is a method of quantitatively compensating for the differential frequency response of sensory systems. Generalized frequency-weighting functions were derived for each functional hearing group of marine mammals using principles from human frequency-weighting paradigms, with adjustments for the different hearing bandwidths of the various marine mammal groups.

For humans, substantial improvement in dose-response models is obtained by filtering noise through equal-loudness functions, particularly the 40-phon, equal-loudness function ("A-weighting") and the 100-phon function ("C-weighting"). These frequency-weighting functions take into account both the frequency bandwidth of human hearing and loudness perception. For use as frequency filters, the functions are inverted; normalized to 0 dB in the frequency range of best hearing (specifically at 1,000 Hz for humans); and idealized for implementation in hearing aids, sound level meters, and other measurement devices.

At minimum, metrics used for animals should eliminate inaudible frequencies both below and above the range of functional hearing. The "absolute" auditory threshold function (audiogram) has been suggested as a frequency-weighting function for marine species exposed to underwater sound (e.g., Malme et al., 1989; Thorson et al., 1998; Heathershaw et al. 2001; Nedwell et al., 2007) as well as for terrestrial animals (Delaney et al., 1999; Bjork et al., 2000). However, the auditory threshold function does not characterize the flattening of equal-loudness perception with the increasing stimulus level that has been demonstrated in humans (Fletcher & Munson, 1933). Acoustic injury would only be expected to occur at levels far above the detection threshold—that is, levels for which the flattening effect would be expected. Consequently, it is unclear how useful or appropriate the auditory threshold function is in deriving frequency-weighting filters in marine mammals for which psychophysical equal-loudness measurements are generally unavailable (although see preliminary measurements by Ridgway & Carder, 2000). Further, the limited TTS data for cetaceans exposed to tones at different frequencies (discussed below) suggest that an audiogram-based frequency-weighting function would produce too much filtering at lower frequencies (i.e., the weighting function for hearing effects should be flatter than the inverted audiogram procedure would indicate).

Therefore, a precautionary procedure was used to derive frequency-specific, marine mammal weighting functions. Each was based on an algorithm that requires only the estimated (as ~80 dB above best hearing sensitivity) lower and upper frequencies of functional hearing as given in the above description of each marine mammal group and in Table 2. The resulting functions were designed to reasonably represent the bandwidth where acoustic exposures can have auditory effects and were designed to be most accurate for describing the adverse effects of high-amplitude noise where loudness functions are expected to flatten significantly. The weighting functions (designated "M" for marine mammal) are analogous to the C-weighting function for humans, which is commonly used in measuring high-amplitude sounds. In the general absence of empirical data, however, the upper and lower frequency roll-offs of the

M-weighting functions are symmetrical, whereas C-weighting admits more energy at the lower than at the upper frequency limits (ANSI, 2001).

The M-weighting functions assume a logarithmic reduction in auditory sensitivity outside of the range of best hearing sensitivity, with the function being 6 dB down from peak sensitivity at the lower and upper frequency "limits." Auditory detection thresholds at these "limits" (see above discussion of lower and upper frequency "cut-offs") can be ≥ 80 dB higher (less sensitive) than those at the frequencies of best hearing sensitivity. Consequently, these frequency filters are much "flatter" than audiograms and probably quite precautionary even considering the expected flattening of equal-loudness contours at high exposure levels. The M-weighting functions are also precautionary in that regions of best hearing sensitivity for most species are likely considerably narrower than the M-weighting functions (designed for the overall marine mammal group) would suggest. The general expression for M-weighting (M[f]), using the estimated lower and upper "functional" hearing limits (f_{low} and f_{high}) for each of the five functional marine mammal hearing groups, is given in Appendix A (eq. 7 & 8). These frequency-weighting functions are identified in Table 2, and each is depicted graphically in Figure 1.

The M-weighting functions de-emphasize frequencies that are near the lower and upper frequency ends of the estimated hearing range as indicated by negative relative values (Figure 1). This de-emphasis is appropriate because, to have a given auditory effect, sound at these frequencies must have higher absolute amplitude than sound in the region of best hearing sensitivity. As a corollary, sound at a given level will have less effect if it is near or (especially) beyond the lower or upper bounds of the functional hearing range than if it is well within that frequency range. It is important to note the incremental nature of the frequency-weighting functions, which approximate the gradual reduction in auditory effect at frequencies outside the range of greatest sensitivity.

Use of such M-frequency-weighting functions is superior to flat weighting across all frequencies because it accounts for known or estimated differences in the frequency response characteristics for each functional hearing group. At least in the context of injury criteria, it is superior to frequency-weighting via the inverse-audiogram method as it takes into account the expected "flattening" of equal-loudness curves at the high exposure levels where TTS and PTS are expected. It is also superior to a "boxcar-type" step function because it more closely approximates the gradual roll-off of sensitivity below and above the range of optimum sensitivity. Furthermore, each of the recommended "shallow" frequency-weighting functions includes, within its relatively flat portion, the full audible range for each species for which auditory data are available. In other words, none of the species included within each functional hearing group has been shown or is expected to have any portion of its best hearing sensitivity outside the flat portion of the relevant frequency-weighting function. Thus, the functions are quite precautionary, which is appropriate given that data are limited or lacking for most species.

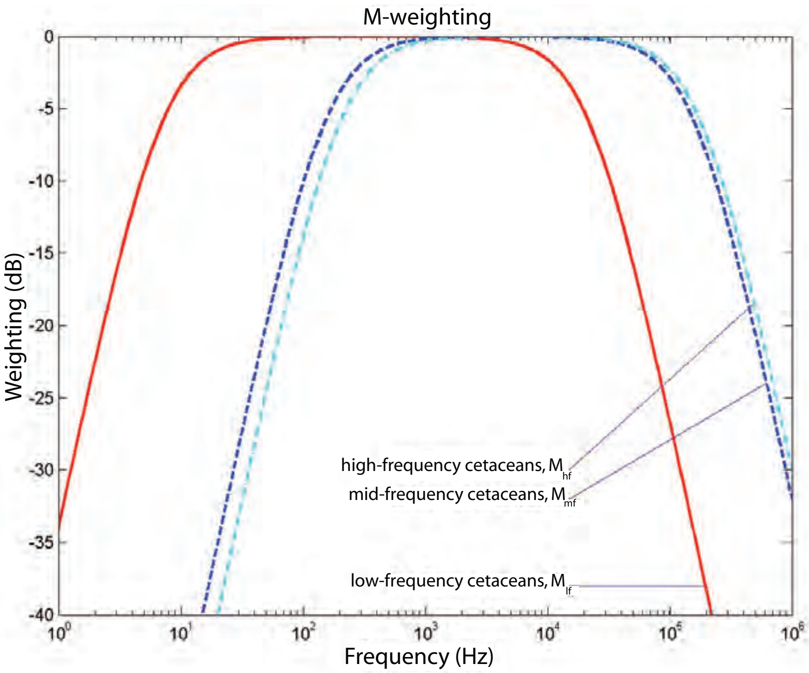
Exposure Criteria Metrics

Many acoustic metrics (e.g., RMS or peak SPL, SEL, kurtosis) could be considered in relation to noise impacts on animals. It is impossible to predict unequivocally which one is best associated with the likelihood of injury or significant behavioral disturbance across all taxa because of species differences and the fact that real-world sound exposures contain many widely differing temporal patterns and pressure signatures. To account for such differences and to allow for current scientific understanding of tissue injury from noise exposure, the proposed injury criteria incorporate a dual-criteria approach based on both peak pressure and energy. For an exposed individual, whichever criterion is exceeded first (i.e., the more precautionary of the two measures) is used as the operative injury criterion. Similarly, a dual-criterion approach (peak sound pressure and energy) is also proposed for behavioral disturbance from a single pulse.

The pressure criteria for injury are defined as those peak SPLs above which tissue injury is predicted to occur, irrespective of exposure duration. Any single exposure at or above this peak pressure is considered to cause tissue injury, regardless of the SPL or SEL of the entire exposure. For each marine mammal group, the recommended pressure-based injury criteria are the same for all sound types and are based on the criterion for a single pulse. This is a precautionary procedure; pressure criteria based on TTS data for nonpulses would yield much higher estimates of the exposure necessary for PTS-onset. By proposing, for all cases, pressure criteria appropriate to a single pulse, we protect against the possibility that, for some sound sources, one or more intense pulses may occasionally be embedded in nonpulse sounds.

For exposures lacking intense peak pressure components, available data indicate that measurements integrating instantaneous pressure squared over the duration of sound exposure are well correlated with the probability of TTS-onset and tissue injury. Consequently, for exposures other than those containing intense peak pressure transients, SEL is the (or at least one of the) appropriate

(A)



(B)

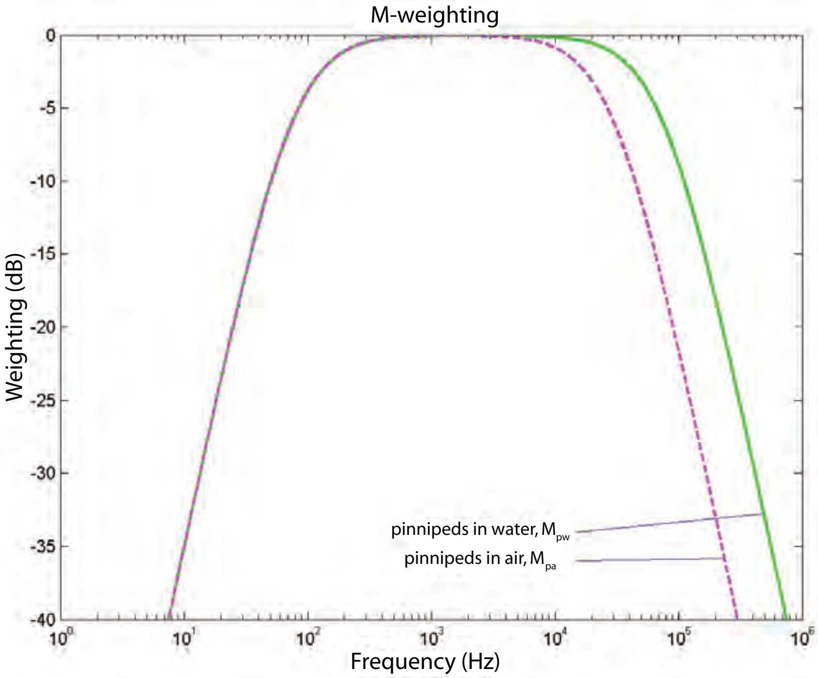


Figure 1. The M-weighting functions for (A) low-, mid-, and high-frequency cetaceans, as well as for (B) pinnipeds in water and air.

metric(s) for estimating TTS-onset and predicting PTS-onset in humans (ISO, 1990).

This use of SEL is based on the assumption that sounds of equivalent energy will have generally similar effects on the auditory systems of exposed human subjects, even if they differ in SPL, duration, and/or temporal exposure pattern (Kryter, 1970; Nielsen et al., 1986; Yost, 1994; NIOSH, 1998). Under the equal-energy assumption, at exposure levels above TTS-onset, each doubling of sound duration is associated with a 3 dB reduction in the SPL theoretically required to cause the same amount of TTS. This relationship has been used in the derivation of exposure guidelines for humans (e.g., NIOSH, 1998). Numerous authors have questioned the predictive power of using a simplistic total energy approach in all conditions. It fails to account for varying levels and temporal patterns of exposure/recovery, among other factors, and will thus likely overestimate the TTS resulting from a complex noise exposure (Hamernik & Hsueh, 1991; Hamernik et al., 1993, 2002; Ahroon et al., 1993; Ward, 1997; Strasser et al., 2003). A comparative assessment of TTS as a function of exposure level in mammals, fish, and birds suggests that there are direct relationships but that the slopes vary among taxa (Smith et al., 2004). The debate over the validity of the equal energy "rule" of noise exposure remains unresolved, even for humans.

Some limited evidence favoring an SEL approach exists for marine mammals, however. Specifically, an equal-energy relationship for TTS-onset appears to hold reasonably well for certain noise exposure types within several mid-frequency cetacean species (Finneran et al., 2002b, 2005a; see "Effects of Noise on Hearing in Marine Animals: TTS Data" section in Chapter 3). A recent study of in-air TTS in a California sea lion (Kastak et al., 2007) illustrates some conditions in which exposures with identical SEL result in considerably different levels of TTS. Nevertheless, because the very limited marine mammal data agree reasonably well (at least as a first-order approximation) with equal-energy predictions, and predictions based on SEL will be precautionary for intermittent exposures, we regard it as appropriate to apply the SEL metric for certain noise exposure criteria until future research indicates an alternate and more specific course. In certain applications, there is much more scientific justification for use of SEL-based criteria than for previous ad hoc SPL criteria (discussed in the "Historical Perspective" section in Chapter 1). In applications involving auditory effects, SEL-based criteria will likely more reliably distinguish cases where phenomena of concern (TTS, PTS, etc.) will and will not likely occur.

Levels of Noise Effect: Injury and Behavioral Disturbance

Direct auditory tissue effects (injury) and behavioral disruption are the two categories of noise effect that are considered in these marine mammal exposure criteria. Chapter 3 summarizes all available data on the effects of noise on marine mammal hearing. It also describes how these data are applied and extrapolated using precautionary measures to predict auditory injury and to derive thresholds and proposed criteria for injury.

In Chapter 4 and Appendices B & C, we summarize the current understanding and available data regarding marine mammal behavioral responses to noise. Chapter 4 includes a quantitative severity scale based generally on the NRC's (2005) Population Consequences of Acoustic Disturbance (PCAD) Model. Chapter 4 also includes a limited and cautious entry of behavioral-response data into a matrix of severity scaling as a function of RL. Currently available data, pooled by functional hearing group, do not support specific numerical criteria for the onset of disturbance. Rather, they indicate the context-specificity of behavioral reactions to noise exposure and point to some general conclusions about response severity in certain, specific conditions.

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3. Criteria for Injury: TTS and PTS

The criteria for injury for all marine mammal groups and sound types are received levels (frequency-weighted where appropriate) that meet the definition of PTS-onset used here (40 dB-TTS, described below). Criteria were derived from measured or assumed TTS-onset thresholds for each marine mammal group plus TTS growth rate estimates (given below). Available TTS data for two mid-frequency cetacean species and three species of pinnipeds are used as the basis for estimating PTS-onset thresholds in all cetaceans ("cetacean procedure" described below; see "PTS-Onset for Pulses") and in all pinnipeds (see "PTS-Onset for Nonpulse Sounds"), respectively. The proposed injury criteria are presented by sound type because, for a given sound type, many of the same extrapolation and summation procedures apply across marine mammal hearing groups.

A dual-criterion approach was used for the recommended injury criteria. That is, any received noise exposure that exceeds either a peak pressure or a SEL criterion for injury is assumed to cause tissue injury in an exposed marine mammal. Of the two measures of sound exposure, peak pressures are to be unweighted (i.e., "flat-weighted"), whereas SEL metrics are to be M-weighted for the relevant marine mammal group (Figure 1). In practice, the received noise conditions should be compared to the two exposure criteria for that sound type and functional hearing group, and the more precautionary of the two outcomes accepted.

Effects of Noise on Hearing in Marine Mammals: TTS Data

Noise exposure criteria for auditory injury ideally should be based on exposures empirically shown to induce PTS-onset; however, no such data presently exist for marine mammals. Instead, PTS-onset must be estimated from TTS-onset measurements and from the rate of TTS growth with increasing exposure levels above the level eliciting TTS-onset. PTS is presumed to be likely if the threshold is reduced by ≥ 40 dB (i.e., 40 dB of TTS). We used available marine mammal TTS data and precautionary extrapolation procedures based on terrestrial mammal data (see "Level of Noise Effect" in Chapter 2) to estimate exposures associated with PTS-onset. Existing TTS measurements for marine mammals are reviewed in detail here since they serve as the quantitative foundation for the injury criteria.

To date, TTSs measured in marine mammals have generally been of small magnitude (mostly < 10 dB). The onset of TTS has been defined as being a temporary elevation of a hearing threshold by 6 dB (e.g., Schlundt et al., 2000), although smaller threshold shifts have been demonstrated to be statistically significant with a sufficient number of samples (e.g., Kastak et al., 1999; Finneran et al., 2005a). Normal threshold variability within and between both experimental and control sessions (no noise) does warrant a TTS-onset criterion at a level that is always clearly distinguishable from that of no effect. We considered a 6 dB TTS sufficient to be recognized as an unequivocal deviation and thus a sufficient definition of TTS-onset.

Most of the frequencies used in TTS experiments to date are within the flat portions of the M-weighting functions given here, but not necessarily within the regions of greatest hearing sensitivity. Within the range of best hearing sensitivity for a given individual, detection thresholds are generally similar. Within this band, exposures with the same absolute level but different frequency are thus similar in terms of their effective sensation level. *Sensation level* is the amount (in dB) by which an RL exceeds the threshold RL for that signal type within a prescribed frequency band (Yost, 2000). If two exposures with identical absolute level are both audible, but one is outside the frequency range of best hearing sensitivity, sensation level will be less for the latter exposure, and its potential effects will be diminished. By creating frequency-weighted functions that are flat across virtually the entire functional hearing band, rather than just the region of best sensitivity, we have made another precautionary decision in the absence of underlying data on equal-loudness functions.

Auditory fatigue (i.e., TTS) in mid-frequency cetaceans has been measured after exposure to tones, impulsive sounds, and octave-band noise (OBN). In pinnipeds, it has been measured upon exposure to construction noise and OBN in both air and water.

Cetacean TTS

The sound exposures that elicit TTS in cetaceans have been measured in two mid-frequency species—bottlenose dolphin and beluga (specific references given below)—with at least limited data being available for exposures to a single pulse and to nonpulsed sounds ranging from 1-s to ~50-min duration. There are no published TTS data for any other odontocete cetaceans (either mid- or high-frequency) or for any mysticete cetaceans (low-frequency). This review is organized according to the duration of the fatiguing stimulus, with shortest exposures discussed first.

Finneran et al. (2000) exposed two bottlenose dolphins and one beluga to single pulses from an "explosion simulator" (ES). The ES consisted of an array of piezoelectric sound projectors that generated a pressure waveform resembling that from a distant underwater explosion. The pressure waveform was generally similar to waveforms predicted by the Navy REFMS model (Britt et al., 1991). The ES failed to produce realistic energy at frequencies below 1 kHz, however. No substantial (i.e., ≥ 6 dB) threshold shifts were observed in any of the subjects exposed to a single pulse at the highest received exposure levels (peak: 70 kPa [10 psi]; peak-to-peak: 221 dB re: 1 μPa (peak-to-peak); SEL: 179 dB re: 1 μPa^2-s)].

Finneran et al. (2002b) repeated this experiment using a seismic watergun that produced a single acoustic pulse. Experimental subjects consisted of one beluga and one bottlenose dolphin. Measured TTS_2 was 7 and 6 dB in the beluga at 0.4 and 30 kHz, respectively, after exposure to intense single pulses (peak: 160 kPa [23 psi]; peak-to-peak: 226 dB re: 1 μPa (peak-to-peak); SEL: 186 dB re: 1 μPa^2-s). Thresholds returned to within ± 2 dB of the pre-exposure value within 4 min of exposure. No TTS was observed in the bottlenose dolphin at the highest exposure condition (peak: 207 kPa [30 psi]; peak-to-peak: 228 dB re: 1 μPa (peak-to-peak); SEL: 188 dB re: 1 μPa^2-s). These studies demonstrated that, for very brief pulses, higher sound pressures were required to induce TTS than had been found for longer tones (discussed below).

Schlundt et al. (2000) reported TTS in five bottlenose dolphins and two belugas exposed to 1-s pure tones (nonpulses). This paper also included a re-analysis of TTS data from a technical report by Ridgway et al. (1997). At frequencies of 3 kHz, 10 kHz, and 20 kHz, SPLs necessary to induce TTS-onset were 192 to 201 dB re: 1 μPa (SEL: 192 to 201 dB re: 1 μPa^2-s). The mean exposure SPL for TTS-onset was 195 dB re: 1 μPa (195 dB re: 1 μPa^2-s). Note the appropriately different metrics for the nonpulse sources used in this study and those involving pulses. Also note that the SPL and SEL values are identical in this special case because of the 1-s duration fatiguing stimuli. At 0.4 kHz, no subjects exhibited shifts after exposures up to SPL exposures of 193 dB re: 1 μPa (193 dB re: 1 μPa^2-s). Data at 75 kHz were inconclusive: one dolphin exhibited a TTS after exposure at 182 dB SPL re: 1 μPa (182 dB re: 1 μPa^2-s) but not at higher exposure levels. The other dolphin experienced no threshold shift after exposure to maximum SPL levels of 193 dB re: 1 μPa (193 dB re: 1 μPa^2-s). The shifts occurred most often at frequencies above the fatiguing stimulus.

Finneran et al. (2005a) measured TTS in bottlenose dolphins exposed to 3 kHz tones with durations of 1, 2, 4, and 8 s and at various SPL values. Tests were conducted in a quiet pool in contrast to previous studies in San Diego Bay, where thresholds were masked by broadband noise. Small amounts of TTS (3 to 6 dB) occurred in one dolphin following exposures with SELs of 190 to 204 dB re: 1 μPa^2-s. These results are consistent with those of Schlundt et al. (2000), indicating that their results had not been significantly affected by the use of masked hearing thresholds in quantifying TTS. In general, the SEL necessary for TTS-onset was relatively consistent across the range of exposure durations, whereas exposure SPL values causing TTS-onset tended to decrease with increasing exposure duration. These results confirmed that, for these testing conditions (bottlenose dolphins exposed to ≤ 8-s tones of variable SPL), TTS magnitude was best correlated with exposure SEL rather than SPL.

Schlundt et al. (2006) reported on the growth and recovery of TTS in a bottlenose dolphin exposed to 3 kHz tones with SPLs up to 200 dB re 1 μPa and durations up to 128 s. The maximum exposure SEL was 217 dB re 1 μPa^2-s, which produced a TTS_4 of ~23 dB. All thresholds recovered to baseline values within 24 h, most within 30 min. The growth of TTS_4 with increasing exposure SEL was ~1 dB TTS per dB SEL for TTS_4 of ~15 to 18 dB.

Finneran et al. (2007b) measured TTS in a bottlenose dolphin after single and multiple exposures to 20 kHz tones. Hearing thresholds were estimated at multiple frequencies (10 to 70 kHz) both behaviorally and electrophysiologically (by measurement of multiple auditory steady-state responses). Three experiments were performed. The first two featured single exposures (20 kHz, 64-s tones at 185 and 186 dB re 1 μPa). The third featured three 20 kHz, 16-s exposures separated by 11 and 12 min, with a mean SPL of 193 dB re 1 μPa (SD = 0.8 dB). Hearing loss was frequency-dependent, with the largest TTS occurring at 30 kHz, less at 40, and then 20 kHz, and little or no TTS at other measured frequencies. AEP threshold shifts reached 40 to 45 dB and were always larger than behavioral shifts, which were 19 to 33 dB. Complete recovery required up to 5 d, with the recovery rate at 20 kHz being ~2 dB/doubling of time and the rate at 30 and 40 kHz ~5 to 6 dB/doubling of time.

Nachtigall et al. (2003) measured TTS (*ca.* 20 min after noise cessation) in a bottlenose dolphin and found an average 11 dB shift following a 30-min net exposure to OBN with a 7.5 kHz center frequency (CF) (max SPL: 179 dB re: 1 µPa; SEL: ~212 to 214 dB re: 1 µPa^2-s). The net exposure time was calculated as the total experimental time minus the time required for the subject to surface to breathe. Exposure during breathing periods was measured and factored into the SEL measurement. No TTS was observed after exposure to the same OBN at maximum SPL values of 165 and 171 dB re: 1 µPa (SEL: ~198 to 200 dB re: 1 µPa^2-s and 204 to 206 dB re: 1 µPa^2-s, respectively).

Using AEP methods, Nachtigall et al. (2004) found TTS$_5$ of *ca.* 4 to 8 dB following nearly 50-min exposures to OBN with a CF of 7.5 kHz (max SPL: 160 dB re: 1 µPa; SEL: ~193 to 195 dB re: 1 µPa^2-s). The difference in results between the two Nachtigall et al. studies (slightly lower TTS after exposure to much lower exposure energy) was attributed to measuring TTS at a shorter interval after the exposure ended (5 vs ~20 min), and thus allowing less opportunity for hearing recovery. Further, Nachtigall et al. (2004) repeatedly measured hearing until recovery had occurred. TTS recovery was shown to occur within minutes or tens of minutes, depending on the amount of the threshold shift. Generally, the recovery rate was 1.5 dB of recovery per doubling of time and was consistent in both studies (Nachtigall et al., 2003, 2004).

The National Research Council (NRC) (1994) identified the need to know whether marine mammals experience greatest TTS at a frequency ½-octave above the frequency of exposure when exposed to loud tones as has been shown in terrestrial mammals. Nachtigall et al. (2004) observed an average threshold shift of 4 dB at 8 kHz but 8 dB shift at 16 kHz following the exposure to OBN centered at 7.5 kHz as described above. A similar upward frequency shift also has been observed by Schlundt et al. (2000) and Finneran et al. (2007b) for mid-frequency cetaceans. These findings provide "strong evidence for fundamental similarities in cochlear micromechanics in marine and land mammals" (NRC, 1994, p. 51) and further justify the judicious extrapolation of TTS data within marine mammal functional hearing groups and from terrestrial to marine mammals.

The above results provide empirical measures of exposure conditions associated with TTS-onset in mid-frequency cetaceans exposed to single pulses and nonpulses. Combined, these data demonstrate that, as compared with the exposure levels necessary to elicit TTS when exposure duration is short, lower SPLs (but similar SEL values) are required to induce TTS when exposure duration is longer. These findings are generally consistent with measurements in humans and terrestrial mammals (Kryter, 1970; Harris, 1998; NIOSH, 1998) and support the use of SEL to approximate the auditory effects of variable exposure level/duration conditions. Although there are certain (possibly many) conditions under which an explicit "equal-energy rule" may fail to adequately describe the auditory effects of variable and/or intermittent noise exposure, the combined cetacean TTS data presented above generally support the use of SEL as a first-order approximation, at least until additional data are available.

For cetaceans, published TTS data are limited to the bottlenose dolphin and beluga (Finneran et al., 2000, 2002b, 2005a; Schlundt et al., 2000; Nachtigall et al., 2003, 2004). Where data exist for both species, we use the more precautionary result (usually for beluga) to represent TTS-onset for all mid-frequency cetaceans. No published data exist on auditory effects of noise in either low- or high-frequency cetaceans (an area of needed research as discussed in Chapter 5); therefore, data from mid-frequency cetaceans are used as surrogates for these two other groups (**cetacean procedure**). [We are aware of some very recent TTS measurements for an individual harbor porpoise exposed to single pulses (Lucke et al., 2007a) but lack sufficient details regarding methodology and data analysis to directly consider those data quantitatively.]

Low-frequency cetaceans (mysticetes), based on their auditory anatomy (Wartzok & Ketten, 1999) and ambient noise levels in the frequency ranges they use (Clark & Ellison, 2004), almost certainly have poorer absolute sensitivity (i.e., higher thresholds) across much of their hearing range than do the mid-frequency species (but see earlier discussion). Mid-frequency cetaceans experience TTS-onset at relatively high levels compared with their absolute hearing sensitivity at similar frequencies (i.e., high sensation levels), although it is not known that this is similarly characteristic of low-frequency cetaceans. Our use of TTS data from mid-frequency cetaceans as a surrogate for low-frequency cetaceans presumes that the two groups have similar auditory mechanisms and are not radically different in relative sensitivity to fatiguing noise, and that relative differences in absolute sensitivity between the two groups are generally as expected.

For high-frequency species, data from mid-frequency cetaceans are currently used as a surrogate in the absence of available group-specific data. Aside from their extended upper-frequency hearing, high-frequency cetaceans appear to be generally similar in auditory anatomy and hearing capabilities to mid-frequency species, though there are some general differences between the groups in sound production. Based on available information and our extrapolation procedures, slightly lower estimates of TTS-onset may be warranted for high-frequency cetaceans exposed to very high-frequency sounds (≥ 100 kHz). [Also, preliminary measurements of TTS in a harbor porpoise exposed to a single airgun pulse (Lucke et al., 2007a) suggest that this species may experience TTS-onset at levels lower than would be suggested by extrapolating from mid-frequency cetaceans. Those results, if confirmed, may provide a more empirical basis for estimating TTS-onset in high-frequency cetaceans and deriving group-specific injury criteria.]

Pinniped TTS (Under Water)

Sound exposures that elicit TTS in pinnipeds under water have been measured in individual subjects of three pinniped species (harbor seal, California sea lion, and northern elephant seal). Available data involved exposures to either broadband or octave-band nonpulse noise over durations ranging from ~12 min to several hours, plus limited data on exposure to underwater pulses. Interestingly, there were consistent among-species differences in the exposure conditions that elicited TTS under water. For the conditions tested, the harbor seal experienced TTS at lower exposure levels than did the California sea lion or northern elephant seal. There are no underwater TTS data for any other pinniped species.

The following review first considers exposure to nonpulses, organized chronologically, followed by a brief discussion of the lone study on exposure to pulses. All but one of the studies (Finneran et al., 2003) came from one laboratory and from the same individual test subjects. Kastak & Schusterman (1996) reported a TTS of ~8 dB (measured under water at 100 Hz) in a harbor seal following exposure to broadband airborne, nonpulse noise from nearby construction. Under controlled conditions, Kastak et al. (1999) measured TTS of *ca.* 4 to 5 dB in a harbor seal, California sea lion, and northern elephant seal following 20- to 22-min exposure to underwater OBN centered at frequencies from 100 Hz to 2 kHz. Exposures were normalized to octave-band levels 60 to 75 dB above each subject's hearing threshold (i.e., 60 to 75 dB sensation level) to present similar effective exposure conditions to each of the three subjects. Because of this approach, absolute exposure values (in terms of both SPL and SEL) were quite variable depending on subject and test frequency.

Subsequently, Kastak et al. (2005) made TTS measurements on the same subjects using 2.5 kHz OBN, higher sensation levels (up to 95 dB), and longer exposure durations (up to 50-min net exposure). These data largely corroborate previous findings concerning TTS-onset in these pinnipeds. They also support sensation level as a relevant metric for normalizing exposures with similar durations across species having different absolute hearing capabilities. Comparative analyses of the combined underwater pinniped data (Kastak et al., 2005) indicated that, in the harbor seal, a TTS of *ca.* 6 dB occurred with 25-min exposure to 2.5 kHz OBN with SPL of 152 dB re: 1 μPa (SEL: 183 dB re: 1 μPa^2-s). Under the same test conditions, a California sea lion showed TTS-onset at 174 dB re: 1 μPa (SEL: 206 dB re: 1 μPa^2-s), and a northern elephant seal experienced TTS-onset at 172 dB re: 1 μPa (SEL: 204 dB re: 1 μPa^2-s).

Data on underwater TTS-onset in pinnipeds exposed to pulses are limited to a single study. Finneran et al. (2003) exposed two California sea lions to single underwater pulses from an arc-gap transducer. They found no measurable TTS following exposures up to 183 dB re: 1 μPa (peak-to-peak) (SEL: 163 dB re: 1 μPa^2-s). Based on the Kastak et al. (2005) measurements using nonpulse sounds, the absence of TTS for the sea lions following such exposures is generally not surprising.

Pinniped TTS (In Air)

Auditory fatigue has been measured following exposure of pinnipeds to single pulses of in-air sound and to nonpulse noise.

Bowles et al. (unpub. data) measured TTS-onset for harbor seals exposed to simulated sonic booms at peak SPLs of 143 dB re: 20 μPa (peak) (SEL: 129 dB re: $[20\ \mu Pa]^2$-s). Higher exposure levels were required to induce TTS-onset in both California sea lions and northern elephant seals in the same test setting, consistent with the results for nonpulse sound both under water and in air.

Auditory fatigue to airborne sound has also been measured in the same three species of pinnipeds after exposure to nonpulse noise, specifically 2.5 kHz CF OBN for 25 min (Kastak et al., 2004a). The harbor seal experienced *ca.* 6 dB of TTS at 99 dB re: 20 μPa (SEL: 131 dB re: $[20\ \mu Pa]^2$-s). Onset of TTS was identified in the California sea lion at 122 dB re: 20 μPa (SEL: 154 dB re: $[20\ \mu Pa]^2$-s). The northern elephant seal experienced TTS-onset at 121 dB re: 20 μPa (SEL: 163 dB re: $[20\ \mu Pa]^2$-s). The subjects in these tests were the same individuals tested in water (Southall et al., 2001; Kastak et al., 2005).

Kastak et al. (2007) measured TTS-onset and growth functions for the same California sea lion exposed to a wider range of noise conditions. A total of 192 exposure sequences were conducted with OBN (centered at 2.5 kHz) at levels 94 to 133 dB re: 20 µPa and durations 1.5 to 50 min net exposure duration. In these more intense noise exposures, TTS magnitudes up to 30 dB were measured at the 2.5 KHz test frequency. Full recovery was observed following all exposures; this occurred rapidly (likely within tens of minutes) for small shifts but took as long as 3 d in the case of the largest TTS. The estimated SEL value coinciding with TTS-onset across these varied exposure conditions was 159 dB re: $(20\ \mu Pa)^2$-s with a TTS growth function of ~2.5 dB TTS/dB noise. For TTS exceeding 20 dB, a recovery rate of ~2.6 dB/doubling of time was calculated. These results generally agree with those of Kastak et al. (2004a) but provide a larger data set, across a wider range of exposure conditions with which to derive an empirical TTS-growth function. They also support the conclusion that patterns of TTS growth and recovery are generally similar to those of terrestrial mammals and that sensation level for the particular species and medium (water or air) is the appropriate metric for comparing the effects of underwater and aerial noise exposure.

Injury from Noise Exposure: PTS-Onset Calculation

As discussed in Chapter 1, PTS is an irreversible elevation of the hearing threshold (i.e., a reduction in sensitivity) at a specific frequency (Yost, 2000). This permanent change following intense noise exposure results from damage or death of inner or outer cochlear hair cells. It is often followed by retrograde neuronal losses and persistent chemical and metabolic cochlear abnormalities (Saunders et al., 1991; Ward, 1997; Yost, 2000).

Noise-induced PTS represents tissue injury, but TTS does not. Although TTS involves reduced hearing sensitivity following exposure, it results primarily from the fatigue (as opposed to loss) of cochlear hair cells and supporting structures and is, by definition, reversible (Nordmann et al., 2000). Many mammals, including some pinnipeds (Kastak et al., 1999, 2005) and cetaceans (e.g., Schlundt et al., 2000; Nachtigall et al., 2004), demonstrate full recovery even after repeated TTS. Since TTS represents a temporary change in sensitivity without permanent damage to sensory cells or support structures, it is not considered to represent tissue injury (Ward, 1997). Instead, the onset of tissue injury from noise exposure is considered here as PTS-onset.

PTS as a function of age (*presbycusis*; discussed in Chapter 1) generally appears to be a normal process of aging in mammals (including humans and marine mammals), but no specific allowance for this is included in our proposed exposure criteria. Data that would be needed to support alternate criteria allowing for presbycusis are lacking. Our approach, which uses TTS data from subjects presumed to have "normal" hearing as the starting point for estimating PTS-onset, is precautionary. It is expected to overestimate damaging effects for those individuals with diminished absolute hearing sensitivity and/or functional bandwidth prior to the exposure.

Data on the effects of noise on terrestrial mammals can be useful in considering the effects on marine mammals in certain conditions (as discussed in Chapter 1) because of similarities in morphology and functional dynamics among mammalian cochleae. Under that premise, it is assumed that a noise exposure capable of inducing 40 dB of TTS will cause PTS-onset in marine mammals. Based on available data for terrestrial mammals, this assumption is likely somewhat precautionary as there is often complete recovery from TTS of this magnitude or greater. Such precaution is appropriate, however, because the precise relationship between TTS and PTS is not fully understood, even for humans and small terrestrial mammals despite hundreds of studies (see Kryter, 1994; Ward, 1997). For marine mammals, this presumably complex relationship is unknown, and likely will remain so. The available marine mammal TTS data provide a basis for establishing a maximum allowable amount of TTS up to which PTS is unlikely, however, and for concluding that PTS is increasingly likely to occur above this point. In using TTS data to estimate the exposure that will cause PTS-onset, our approach is to acknowledge scientific uncertainty and to err on the side of overestimating the possibility of PTS (i.e., on the side of underestimating the exposure required to cause PTS-onset).

In humans, when TTS_2 magnitude for a single exposure exceeds *ca.* 40 dB, the likelihood of PTS begins to increase substantially (Kryter et al., 1966; Kryter, 1994). Threshold shifts greater than 40 dB have been demonstrated to be fully recoverable after some period of time in some terrestrial mammal species (human: Ward, 1959; Ahroon et al., 1996; chinchilla: Miller et al., 1971; Mongolian gerbil [*Meriones unguiculatus*]: Boettcher, 1993). Generally, however, TTS exceeding 40 dB requires a longer recovery time than smaller shifts, suggesting a higher probability of irreversible damage (Ward, 1970) and possibly different underlying mechanisms (Kryter, 1994; Nordman et al., 2000).

Our derivation of proposed injury criteria for marine mammals begins with measured or estimated noise exposure conditions associated with TTS-onset in cetaceans and pinnipeds. Procedures for estimating PTS-onset, assumed to occur in conditions causing 40 dB of TTS, were derived by combining (1) measured or estimated TTS-onset levels in marine mammals and (2) the estimated "growth" of TTS in certain terrestrial mammals exposed to increasing noise levels. The general PTS-onset procedures differ according to sound type (pulses and nonpulses), the extent of available information, and required extrapolation. To estimate exposure conditions that will result in PTS-onset, SEL and SPL were considered separately.

PTS-Onset for Pulses

Henderson & Hamernik (1986) reported that in chinchillas exposed to pulses up to a certain level, for each dB of added exposure above that which caused TTS-onset, a further TTS of about 0.5 dB resulted. For the highest exposure levels, as much as 3 dB of additional TTS was found per additional dB of noise. Thus, in extrapolating TTS growth functions from terrestrial to marine mammals, a precautionary approach is justified such as using a slope nearer the upper extreme of this range to estimate the growth of TTS with exposure level.

When dealing with pulsed sound, to estimate SEL exposures coincident with PTS-onset, we assume a slope of 2.3 dB TTS/dB noise. This is relatively precautionary in relation to the data by Henderson & Hamernik (1986) on chinchillas. This slope translates to an injury criterion (for pulses) that is 15 dB above the SEL of exposures causing TTS-onset (defined above as 6 dB TTS). That is, PTS-onset (40 dB TTS) is expected to occur on exposure to an M-weighted SEL 15 dB above that associated with TTS-onset ([40 dB TTS – 6 dB TTS] / [2.3 dB TTS/dB noise exposure] ≈ 15 dB noise exposure above TTS-onset).

In terms of sound pressure, TTS-onset thresholds in marine mammals, particularly cetaceans, are quite high (see above). The predicted PTS-onset values would be very high (perhaps unrealistically so as they would approach the cavitation limit of water) if the aforementioned 15 dB difference between TTS-onset and PTS-onset were assumed. Consequently, an additional precautionary measure was applied by arbitrarily assuming that the pressure difference between TTS-onset and PTS-onset for pulses might be just 6 dB. This results in a TTS "growth" relationship of 6 dB TTS/dB noise (i.e., [40 dB TTS – 6 dB TTS] / [6 dB TTS/dB noise exposure] ≈ 6 dB noise exposure above TTS-onset). That is an extremely conservative slope function given that it is double the highest rate found in chinchillas by Henderson & Hamernik (1986). This 6 dB of added exposure, above the exposure eliciting TTS-onset, essentially establishes a proposed (unweighted) peak-pressure ceiling value for all sound types.

PTS-Onset for Nonpulse Sounds

The peak pressure values assumed to be associated with onset of injury (PTS-onset) are numerically equivalent for nonpulse and pulse sounds. Among other considerations, this allows for the possibility that isolated pulses could be embedded within the predominantly nonpulse sound.

To estimate the SEL value that would cause PTS-onset for nonpulse sounds, we used the following procedure. In humans, each added dB of nonpulse noise exposure above TTS-onset results in up to 1.6 dB of additional TTS (Ward et al., 1958, 1959). Assuming this relationship applies to marine mammals, ~20 dB of additional noise exposure above that causing TTS-onset is required to induce PTS-onset (i.e., [40 dB TTS – 6 dB TTS] / [1.6 dB TTS/dB noise exposure] = 21.3 dB of additional noise exposure). We rounded this down to a slightly more precautionary value of 20 dB of additional noise exposure above TTS-onset. Consequently, to estimate PTS-onset and derive the SEL injury criteria for nonpulses, we add 20 dB to the M-weighted SEL values estimated to cause TTS-onset. The lone exception to this approach is for pinnipeds in air (discussed below) where a more precautionary TTS growth rate was used based on a relatively large empirical data set (Kastak et al., 2007).

Criteria for Injury from a Single Pulse

As per the "PTS-Onset Calculation" section of this chapter, the recommended criteria for injury from exposure to a single pulse, expressed in terms of peak pressure, are TTS-onset levels plus 6 dB of additional exposure. In terms of SEL, the recommended criteria are TTS-onset levels plus 15 dB of additional exposure.

For all cetaceans exposed to pulses, the data of Finneran et al. (2002b) were used as the basis for estimating exposures that would lead to TTS-onset (and, consequently, PTS-onset). They estimated that, in a beluga exposed to a single pulse, TTS-onset occurred with unweighted peak levels of 224 dB re: 1 μPa (peak) and 186 dB re: 1 μPa^2-s. The latter is equivalent to a weighted (M_{mf}) SEL exposure of 183 dB re: 1 μPa^2-s as some of the energy in the pulse was at low frequencies to which the beluga is less sensitive. Adding 6 dB to the former (224 dB) values, the pressure criterion for injury for mid-frequency cetaceans is therefore 230 dB re: 1 μPa (peak) (Table 3, Cell 4). Adding 15 dB to the latter (183 dB) value, the M-weighted SEL injury criterion is 198 dB re: 1 μPa^2-s (Table 3, Cell 4). These results are assumed to apply (see cetacean procedure, p. 439) to low- and perhaps high-frequency cetaceans (Table 3, Cells 1 & 7, respectively) as well as to mid-frequency cetaceans. These injury criteria, expressed in SEL, are slightly more precautionary than, but generally consistent with, Ketten's 1998 prediction (pers. comm.) that 30% of individual cetaceans exposed to pulses with an SEL of 205 dB re: 1 µPa^2-s would experience PTS.

For pinnipeds in water, there are no empirical data concerning the levels of single pulses that would lead to TTS-onset. At least for the California sea lion, the required exposure is expected to be greater than 183 dB re: 1 µPa (peak) and 163 dB re: 1 µPa^2-s) because Finneran et al. (2003) found no TTS in two California sea lions following such exposures. In the absence of specific data on the level of a sound pulse that would cause TTS-onset for pinnipeds in water, we used a three-step process to estimate this value:

(1) We began with the Finneran et al. (2002b) data on TTS-onset from single pulse exposures in a mid-frequency cetacean. TTS-onset occurred with a peak pressure of 224 dB re: 1 µPa (peak) and M_{mf}-weighted SEL of 183 dB re: 1 µPa^2-s.

(2) We assumed that the known pinniped-to-cetacean difference in TTS-onset upon exposure to nonpulse sounds would also apply (in a relative sense) to pulses. Specifically, with nonpulse sounds, harbor seals experience TTS-onset at *ca.* 12 dB lower RLs than do belugas (i.e., 183 vs 195 dB re: 1 µPa^2-s; Kastak et al., 1999, 2005; Southall et al., 2001; Schusterman et al., 2003 vs Finneran et al., 2000, 2005a; Schlundt et al., 2000; Nachtigall et al., 2003, 2004). Assuming that this difference for nonpulse sounds exists for pulses as well, TTS-onset in pinnipeds exposed to single underwater pulses is estimated to occur at a peak pressure of 212 dB re: 1 µPa (peak) and/or an SEL exposure of 171 dB re: 1 µPa^2-s. Each of these metrics is 12 dB less than the comparable value for mid-frequency cetaceans (see Finneran et al., 2002b, and above).

(3) As per the "PTS-onset Procedure" (discussed earlier), we added 6 dB to the former (212 dB) value to derive the recommended injury pressure criterion of 218 dB re: 1 µPa (peak) (unweighted) for pinnipeds in water exposed to a single pulse. Similarly, we added 15 dB to the latter value (171 dB) to derive the recommended M-weighted SEL injury criterion of 186 dB re: 1 µPa^2-s (Table 3, Cell 10). These proposed criteria are likely precautionary because the harbor seal is the most sensitive pinniped species tested to date, based on results from a single individual (Kastak et al., 1999, 2005).

For pinnipeds in air exposed to a single sound pulse, the proposed criteria for injury were based on measurements by Bowles et al. (unpub. data), which indicated that TTS-onset in harbor

Table 3. Proposed injury criteria for individual marine mammals exposed to "discrete" noise events (either single or multiple exposures within a 24-h period; see Chapter 2)

	Sound type		
Marine mammal group	Single pulses	Multiple pulses	Nonpulses
Low-frequency cetaceans	Cell 1	Cell 2	Cell 3
Sound pressure level	230 dB re: 1 µPa (peak) (flat)	230 dB re: 1 µPa (peak) (flat)	230 dB re: 1 µPa (peak) (flat)
Sound exposure level	198 dB re: 1 µPa^2-s (M_{lf})	198 dB re: 1 µPa^2-s (M_{lf})	215 dB re: 1 µPa^2-s (M_{lf})
Mid-frequency cetaceans	Cell 4	Cell 5	Cell 6
Sound pressure level	230 dB re: 1 µPa (peak) (flat)	230 dB re: 1 µPa (peak) (flat)	230 dB re: 1 µPa (peak) (flat)
Sound exposure level	198 dB re: 1 µPa^2-s (M_{mf})	198 dB re: 1 µPa^2-s (M_{mf})	215 dB re: 1 µPa^2-s (M_{mf})
High-frequency cetaceans	Cell 7	Cell 8	Cell 9
Sound pressure level	230 dB re: 1 µPa (peak) (flat)	230 dB re: 1 µPa (peak) (flat)	230 dB re: 1 µPa (peak) (flat)
Sound exposure level	198 dB re: 1 µPa^2-s (M_{hf})	198 dB re: 1 µPa^2-s (M_{hf})	215 dB re: 1 µPa^2-s (M_{hf})
Pinnipeds (in water)	Cell 10	Cell 11	Cell 12
Sound pressure level	218 dB re: 1 µPa (peak) (flat)	218 dB re: 1 µPa (peak) (flat)	218 dB re: 1 µPa (peak) (flat)
Sound exposure level	186 dB re: 1 µPa^2-s (M_{pw})	186 dB re: 1 µPa^2-s (M_{pw})	203 dB re: 1 µPa^2-s (M_{pw})
Pinnipeds (in air)	Cell 13	Cell 14	Cell 15
Sound pressure level	149 dB re: 20 µPa (peak) (flat)	149 dB re: 20 µPa (peak) (flat)	149 dB re: 20 µPa (peak) (flat)
Sound exposure level	144 dB re: (20 µPa)^2-s (M_{pa})	144 dB re: (20 µPa)^2-s (M_{pa})	144.5 dB re: (20 µPa)^2-s (M_{pa})

Note: All criteria in the "Sound pressure level" lines are based on the peak pressure known or assumed to elicit TTS-onset, plus 6 dB. Criteria in the "Sound exposure level" lines are based on the SEL eliciting TTS-onset plus (1) 15 dB for any type of marine mammal exposed to single or multiple pulses, (2) 20 dB for cetaceans or pinnipeds in water exposed to nonpulses, or (3) 13.5 dB for pinnipeds in air exposed to nonpulses. See text for details and derivation.

seals occurs following exposure to 143 dB re: 20 µPa (peak) and 129 dB re: (20 µPa)^2-s. As for underwater exposures to nonpulse sounds (Kastak et al., 1999, 2005), higher exposure levels were required to induce TTS in California sea lions and northern elephant seals. Consequently, using harbor seal TTS data to establish injury criteria for exposure to a single aerial pulse in pinnipeds is likely a precautionary approximation. Based on these estimates of peak pressure and SEL associated with TTS-onset, plus 6 dB and 15 dB, respectively, to estimate PTS-onset, the injury criteria for pinnipeds exposed to a single aerial pulse are 149 dB re: 20 µPa (peak) (unweighted) and 144 dB re: (20 µPa)^2-s, M-weighted (Table 3, Cell 13).

Criteria for Injury from Multiple Pulses

For all marine mammal groups, the recommended criteria for exposure to multiple pulses, expressed in both SPL and SEL units, were numerically identical to the criteria for a single pulse. Any exposure in a series that exceeds the peak pressure criterion would be considered potentially injurious. In addition, the cumulative SEL for multiple exposures should be calculated using the summation technique described in Chapter 1 (Appendix A, eq. 5). The resulting SEL value for multiple pulses is then compared to the SEL injury criterion for a single pulse in the same functional hearing group. As for the single pulse criteria, peak pressures are unweighted (i.e., "flat-weighted"), but SEL should be weighted by the appropriate M-weighting function (Figure 1).

For cetaceans, the proposed criteria for injury by multiple pulses are therefore 230 dB re: 1 µPa (peak) and, following summation, 198 dB re: 1 µPa^2-s in terms of SEL (Table 3, Cells 2, 5 & 8). As for single pulses, this approach is considered precautionary for mid- and low-frequency species, but some caution is warranted in applying it to high-frequency species (*cf.* Lucke et al., 2007a).

Following the same logic, the proposed injury pressure criterion for pinnipeds in water exposed to multiple pulses is 218 dB re: 1 µPa (peak) and the injury SEL criterion is 186 dB re: 1 µPa^2-s (Table 3, Cell 11). For pinnipeds in air, the proposed injury pressure criterion for multiple pulses is 149 dB re: 20 µPa (peak) and the injury SEL criterion is 144 dB re: (20 µPa)^2-s (Table 3, Cell 14).

Criteria for Injury from Nonpulses

SPL and SEL appear to be appropriate metrics for quantifying exposure to nonpulse sounds. But because SPL measures involve averaging over some duration, they may not adequately quantify high peak pressure transients embedded within exposures of longer duration but lower-pressure magnitude. There are related limitations with SEL in that temporal integration is involved.

To account for the potentially damaging aspects of high-pressure transients embedded within nonpulse exposures, a precautionary approach was taken, and the same peak pressure criterion for injury proposed for single pulses is also recommended as the criterion for multiple pulses in all functional hearing groups. Thus, if any component of a nonpulse exposure (unweighted) exceeds the peak pressure criterion, injury is assumed to occur. We expect that only rarely will the injury pressure criterion for nonpulse sound be exceeded if the injury SEL criterion is not exceeded (i.e., the SEL criterion will be the effective criterion in most exposure conditions).

For nonpulsed sounds, the recommended SEL criteria for injury (PTS-onset) are M-weighted exposures 20 dB higher than those required for TTS-onset (see "PTS-Onset Calculation: Nonpulses"). Injury SEL criteria for multiple nonpulses are numerically identical to those for single nonpulses for all hearing groups. We make no distinction between single and multiple nonpulses except that the cumulative SEL for multiple exposures is calculated as described in Chapter 1 and Appendix A, eq. 5.

For all cetaceans exposed to nonpulses, the recommended pressure criterion for injury is 230 dB re: 1 µPa (peak) (Table 3, Cells 3, 6, & 9), the same criterion as for single pulses in these functional hearing groups. Injury SEL criteria are based on TTS data for mid-frequency species and extrapolated to the other cetacean groups (see cetacean procedure, p. 439). The SEL criterion for nonpulse injury in cetaceans is calculated to be an M-weighted exposure of 215 dB re: 1 µPa^2-s (Table 3, Cells 3, 6 & 9). This is based on 195 dB re: 1 µPa^2-s as an estimate of TTS-onset in mid-frequency cetaceans (Finneran et al., 2002b, 2005a; Schlundt et al., 2000; Nachtigall et al., 2003, 2004) plus 20 dB to estimate PTS-onset. Applying this approach to low-frequency cetaceans is considered precautionary, but some caution may be warranted in extrapolating to high-frequency cetaceans (*cf.* single-pulse data of Lucke et al., 2007a).

We note that special injury criteria, different from those shown in Cell 6 of Table 3, are likely needed for exposure of beaked whale species to nonpulses. Under certain conditions, beaked whales of several species (primarily Cuvier's, Blainville's, and Gervais' beaked whales) have stranded in the presence of sound signals from tactical mid-frequency military sonars (Frantzis, 1998; Evans & England, 2001; Fernández et al., 2005; Cox et al., 2006). There have been other incidents (e.g., NMFS, 2005; Hohn et al., 2006) where marine mammal strandings or other anomalous events involving other marine mammal species have occurred in association with mid-frequency sonar operations. They are, however, much more ambiguous, difficult to interpret, and appear fundamentally different than the specific beaked whale events. Little is known about the exposure levels, or about the positions or reactions of other marine mammals in the areas during mid-frequency sonar training operations. The most extreme, ultimate response of some beaked whales in specific conditions (stranding and subsequent death) does not appear to be typical of other marine mammals.

Sound fields resulting from sonar operations have been modeled in several of the above cases (e.g., the 1996 event in Greece and the 2000 event in the Bahamas), and it is possible to at least roughly bound the estimated exposures for some of the individuals that stranded (D'Spain et al., 2006). While the specific exposure levels will never be quantitatively known, it does appear likely that the exposures for some of the beaked whales that stranded were below the criteria for tissue injury proposed above.

Consequently, the general injury criteria do not seem sufficiently precautionary for beaked whales exposed to some nonpulse sounds under certain conditions. Empirical data to support discrete, science-based injury criteria specific to beaked whales exposed to tactical, mid-frequency, military sonar are lacking, however. Regulatory agencies should consider adopting provisional injury criteria for beaked whales exposed to active, mid-frequency, military sonars that are lower (in terms of RL) than the criteria used for mid-frequency cetaceans and nonpulse sources generally. Of foremost importance, specific studies are needed to better define the mechanism of injury in these apparently sensitive species (see Chapter 5).

For pinnipeds in water, the recommended pressure criterion for injury from exposure to nonpulse sounds is the same value as applied to pulses: an unweighted value of 218 dB re: 1 µPa (peak) (Table 3, Cell 12). To derive the associated SEL criterion, we began with the measured nonpulse exposure eliciting TTS-onset in a harbor seal, 183 dB re: 1 µPa^2-s (Kastak et al., 1999, 2005). This is likely a precautionary choice because SEL values ~10 to 20 dB higher were required to induce TTS-onset in a California sea lion and a northern elephant seal. We assume that 20 dB of additional noise exposure will elicit PTS-onset (see "Effects of Noise on Hearing" section of this chapter), resulting in an M_{pw}-weighted SEL criterion of 203 dB re: 1 µPa^2-s for pinnipeds exposed to nonpulse sound in water (Table 3, Cell 12).

For pinnipeds in air exposed to nonpulse sound, the injury pressure criterion is a flat-weighted value of 149 dB re: 20 µPa (peak) (Table 3, Cell 15), consistent with that for pulses. The SEL criterion is based on occurrence of TTS-onset in a harbor seal exposed in air to 131 dB re: (20 µPa)^2-s (Kastak et al., 2004a). In estimating the exposure that would cause PTS-onset, we use empirical measurements of TTS growth as a function of exposure SEL in a California sea lion. Kastak et al. (2007) found a TTS growth rate of 2.5 dB TTS/dB noise based on nearly 200 exposure sequences involving variable exposure level and duration conditions. This growth rate implies a 13.5 dB difference between TTS- and PTS-onset as opposed to the 20 dB value used for marine mammals in water. When the 13.5 dB figure is added to the TTS-onset value for harbor seals (131 dB re: [20 µPa]^2-s), we obtain a proposed M_{pa}-weighted SEL criterion of 144.5 dB re: (20 µPa)^2-s for pinnipeds in air (Table 3, Cell 15).

The use for all pinnipeds of harbor seal TTS data combined with the sea lion growth function would be an exceedingly precautionary procedure. This PTS-onset estimate is considerably below the TTS-onset estimates for both the northern elephant seal (163 dB re: [20 µPa]^2-s; Kastak et al., 2004a) and the California sea lion (159 dB re: [20 µPa]^2-s; Kastak et al., 2007). Applying the TTS growth function of 2.5 dB TTS/dB noise from Kastak et al. (2007) to these TTS-onset estimates would yield PTS-onset values of 172.5 and 176.5 dB re: (20 µPa)^2-s for the California sea lion and northern elephant seal, respectively. As noted in the "Overview," where specific data are available for the species or genus of concern, it is appropriate for criteria to be based on those data rather than the generalized criteria that are recommended for the overall group of marine mammals.

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4. Criteria for Behavioral Disturbance

Behavioral reactions to acoustic exposure are generally more variable, context-dependent, and less predictable than effects of noise exposure on hearing or physiology. Animals detecting one kind of signal may simply orient to hear it, whereas they might panic and flee for many hours upon hearing a different sound, potentially even one that is quieter, but with some particular significance to the animal. The conservation of cochlear properties across mammals justifies judicious application of auditory data from terrestrial mammals where data on marine mammals are missing. However, the context-specificity of behavioral responses in animals generally makes extrapolation of behavioral data inappropriate. Assessing the severity of behavioral disturbance must consequently rely more on empirical studies with carefully controlled acoustic, contextual, and response variables than on extrapolations based on shared phylogeny or morphology.

Considerable research has been conducted to describe the behavioral responses of marine mammals to various sound sources. Fortunately, at least limited data are available on behavioral responses by each of the five functional marine mammal groups to each sound type considered here. As evident in the extensive literature review summarized below and described in detail in Appendices B & C, however, very few studies involving sufficient controls and measurements exist. In addition, the influence of experience with the experimental stimulus or similar sounds has usually been unknown.

To assess and quantify adverse behavioral effects of noise exposure, a metric for the impact such changes might have on critical biological parameters such as growth, survival, and reproduction is needed. Behavioral disturbances that affect these vital rates have been identified as particularly important in assessing the significance of noise exposure (NRC, 2005). Unfortunately, as Wartzok et al. (2004) pointed out, no such metric is currently available, and it is likely to take decades of research to provide the analytical framework and empirical results needed to create such a metric, if one in fact is ultimately even viable.

In humans, a common and useful means of estimating behavioral disturbance from noise exposure is to ask individuals to rate or describe the degree to which various sounds are bothersome. Subjective perception of noise "annoyance" has been quantified (e.g., Schultz, 1978; Angerer et al., 1991) and used to develop dose-response relationships for noise exposure in human community noise applications (see Kryter, 1994, Chapter 10). Practical issues (e.g., difficulties in training nonverbal species to provide interpretable responses and questions about the applicability of captive data to free-ranging animals) have prevented this or similar approaches from being applied to marine mammals. Instead, most efforts have focused on analyses of observable reactions to known noise exposure.

For most free-ranging marine mammals, behavioral responses are often difficult to observe. Also, precise measurements of received noise exposure and other relevant variables (e.g., movement of source, presence of high-frequency harmonics indicating relative proximity, and prior experience of exposed individuals) can be difficult to obtain. Only a subset of disturbance studies have estimated received sound levels, and only a very small number have actually measured RLs at the subject. Further, exposures are often complicated by multiple contextual covariants such as the presence of vessels and/or humans close to subjects either for observation or to deploy playback sources (e.g., Frankel & Clark, 1998). Interpretation of the observed results is highly limited by uncertainty as to what does and does not constitute a meaningful response. Also, most behavioral-response studies have concentrated on short-term and localized behavioral changes whose relevance to individual well-being and fitness, let alone population parameters, is likely to be low.

A further complication is that observations from laboratory and field settings cannot be directly equated. Laboratory studies are usually precise in quantifying exposures and responses. The exposure conditions very rarely approximate those in the field, however, and measured behavior may have little or no relevance to the ways in which unconstrained, untrained wild animals respond. Conversely, field measurements may address responses of free-ranging mammals to a specific sound source but often lack adequate controls and precision in quantifying acoustic exposures and responses. Clearly, there is a need for a framework to integrate laboratory and field data, despite the challenges in constructing that framework.

Another difficult issue concerns the appropriate noise exposure metric for assessing behavioral reactions. Most bioacousticians recommend reporting several different measures of acoustic exposure, such as SPL and SEL (as in Blackwell et al., 2004a, 2004b). Of the many studies that report source SPL, relatively few specify whether RMS, peak, peak-to-peak, or other sound pressure measurements were made. Additionally, relatively few papers provide sufficient relevant information about sound transmission loss in the study area. A small number of papers report estimates or direct measurements of received SPL, but very few report SEL. The appropriate measure for predicting probability of a behavioral response is likely to vary depending upon the behavioral context. For example, if an animal interprets a sound as indicating the presence of a predator, a short faint signal may evoke as strong a response as a longer, strong sound. But if an animal is responding to a context-neutral stimulus that is merely annoying, the probability of response may well scale with duration and level of exposure.

It is difficult to define the SEL for individual animals in the wild exposed to a specific sound source. Ideally, received SEL over the animal's full duration of exposure would be measured (Madsen et al., 2005a). We expect that the probability and severity of some kinds of response will vary with duration as well as level of exposure; for those situations, an SEL metric may be most appropriate. However, the most practical way to look for consistent patterns of response as a function of RL and duration, given the current state of science, is to evaluate how different animals respond to similar sound sources used in similar contexts. For example, the relationship between acoustic exposure and animal responses is likely to be quite different for mammals exposed to sounds from a slow-moving seismic survey vessel operating in a given habitat for many weeks as compared with a torpedo transmitting directional high-frequency sonar pings as it transits an area once at many tens of knots. Similarly, an acoustic harassment device placed in a habitat for years is likely to evoke a different severity of response than would several short pulses at a comparable SPL. Until more controlled studies become available with calibrated measurements of RLs and ambient noise measurements (including signal-to-noise ratio), the best way to predict likely effects will be a common-sense approach that assesses available data from situations similar to the situation of concern.

Considering all of these limitations and the nature of the available data, as a practical matter, we use SPL as the acoustic metric for the behavioral analyses given below. Where necessary and appropriate, simple assumptions regarding transmission loss were applied to predict RLs. This was done only for studies that provided sufficient information on source and environmental characteristics. Our approach does not presume that SPL is necessarily the acoustic metric best correlated with behavioral changes (significant or otherwise). In particular, SPL fails to account for the duration of exposure whereas this is captured using SEL. SPL is the metric that has most often been measured or estimated during disturbance studies, however. Thus, it is currently the best metric with which to assess the available behavioral response data. Future studies should report the full range of standard acoustic measurements appropriate to the sound source in question and should also include measurements of background noise levels in order to assess signal-to-noise ratios. These additional data should eventually clarify which exposure metrics best predict different kinds of behavioral responses and which are most appropriate for use in policy guidelines applicable to different types of noise exposures.

Beyond the discussion of which metric is most appropriate to quantify the exposure level of a sound, it is recognized that many other variables affect the nature and extent of responses to a particular stimulus. Wartzok et al. (2004) discussed in detail the highly variable response of belugas exposed to similar sounds in different locations—for example, Frost et al. (1984) vs Finley et al. (1990). In those cases, it appears that the context (recent experience of the belugas with the sound stimulus, their current activity, and their motivation to remain or leave) was much more significant in governing their behavioral responses. Similarly, reactions of bowhead whales to seismic airgun sounds depend on whether the whales are feeding (Richardson et al., 1986; Miller et al., 2005) vs migrating (Richardson et al., 1999). Reactions of bowheads and other cetaceans to boats depend on whether the boats are moving or stationary, and on the relative movement of the boat and the whale (see Richardson et al., 1995; Wartzok et al., 2004). In these and some other cases, simple metrics of exposure (without considering context) will not reliably predict the type and severity of behavioral response(s). Our analyses here, which use exposure SPL alone, are admittedly rudimentary and limited by the fact that—for most species and situations—current data do not support a more sophisticated approach.

Another key consideration involves differentiating brief, minor, biologically unimportant reactions from profound, sustained, and/or biologically meaningful responses related to growth, survival, and reproduction. The biological relevance of a behavioral response to noise exposure may depend in part on how long it persists. Many mammals perform vital functions (e.g., feeding, resting, traveling, socializing) on a diel cycle. Repeated or sustained disruption of these functions is more likely to have a demonstrable effect on vital rates than a single, brief disturbance episode. The NRC (2005) argued that, although the duration of behaviors likely to affect vital rates is believed to be particularly significant, current scientific knowledge is insufficient to support an analytical treatment of biological significance and ad hoc criteria are needed in the interim. Here, substantive behavioral reactions to noise exposure (such as disruption of critical life functions, displacement, or avoidance of important habitat) are considered more likely to be significant if they last more than one diel period, or recur on subsequent days. Consequently, a reaction lasting less than 24 h and not recurring on subsequent days is not regarded as particularly severe unless it could directly affect survival or reproduction.

In the absence of an overarching means of quantifying the biological significance of an effect, we had to adopt a more descriptive method of assessing the range of possible responses and the severity of behavioral response. To do this, we took two different approaches. For the unusual case of exposure to a single pulse, where the exposure is very brief and responses are usually brief as well, a procedure for determining recommended criteria is identified and applied. For all other conditions, an ordinal and subjective response severity scaling was developed and applied to those data on marine mammal behavioral responses for which estimates of received SPL were available. These analyses were limited to peer-reviewed literature (published or in press) and peer-reviewed technical reports, with some exceptions on a case-by-case basis.

The severity scale was designed to provide some analytical basis for assessing biological significance, but it had to be rooted in the kinds of descriptions provided in the available scientific literature. Our current understanding of the influences of contextual variables on behavioral responses in free-ranging marine mammals is very limited. The analyses presented here should be considered with these cautions and caveats in mind. Our goal was to review the relevant scientific literature, tally behavioral effects by the type of acoustic exposure for each category of marine mammal and sound type, and draw what conclusions were appropriate based on the information available.

The general procedures for determining behavioral response exposure criteria for a single pulse, and for conducting the severity analyses of individual behavioral responses vs received SPL, are discussed in the next section. Subsequent sections discuss the exposure criterion levels for single pulses and summarize the literature considered in the severity scaling analyses for multiple pulses and nonpulse sources. More detailed discussions of this literature are given in Appendix B for multiple pulses and Appendix C for nonpulse sources.

Behavioral Response Data Analysis Procedures: Disturbance Criteria and Severity Scaling

Single Pulse

Due to the transient nature of a single pulse, the most severe behavioral reactions will usually be temporary responses, such as startle, rather than prolonged effects, such as modified habitat utilization. A transient behavioral response to a single pulse is unlikely to result in demonstrable effects on individual growth, survival, or reproduction. Consequently, for the unique condition of a single pulse, an auditory effect is used as a *de facto* disturbance criterion. It is assumed that significant behavioral disturbance might occur if noise exposure is sufficient to have a measurable transient effect on hearing (i.e., TTS-onset). Although TTS is not a behavioral effect per se, this approach is used because any compromise, even temporarily, to hearing functions has the potential to affect vital rates by interfering with essential communication and/or detection capabilities. This approach is expected to be precautionary because TTS at onset levels is unlikely to last a full diel cycle or to have serious biological consequences during the time TTS persists. Because this approach is based on an auditory phenomenon, the exposure criteria can reasonably be developed for entire functional hearing groups (as in the injury criteria) rather than on a species-by-species basis. The extrapolation procedures used to estimate TTS-onset for single pulse exposures for each hearing group are described in Chapter 3 (see the "Injury from Noise Exposure: PTS-Onset Calculation" section).

A dual-criterion approach (using both SPL [peak] and SEL) was used to determine behavioral criteria for a single pulse exposure. Consistent with the injury criteria, which also were based on auditory fatigue data, RLs that exceed the criterion for either metric are considered to have greater potential to elicit a biologically significant behavioral response. Proposed criteria for exposure to a single pulse for each functional hearing group are given in the next section. These criteria are the TTS-onset thresholds discussed in Chapter 3.

An exception was made in any case where behavioral data indicate that a single pulse exposure may elicit a sustained and potentially significant response when the RL is below that required for TTS-onset. This can apply to hauled-out pinnipeds, which sometimes stampede from a beach upon exposure to a sonic boom and may not return for many hours (e.g., Holst et al., 2005a, 2005b). In cases where such behavioral responses may result in the injury or death of pups or other individuals, exposure levels should be considered in the context of injury criteria. Conversely, if available behavioral data indicate that the response threshold for exposure to a single pulse is above the level required for TTS-onset, then the TTS-onset level is retained as the behavioral criterion as a further precautionary procedure.

Multiple Pulses and Nonpulses

For all other sound types than single pulses, we expect that significant behavioral effects will occur more commonly at levels below those involved in temporary or permanent losses of hearing sensitivity. This argues against basing threshold criteria exclusively on TTS and indicates the need for a paradigm to predict the probability of significant behavioral response as a function of noise exposure. However, because of the extreme degree of group, species, and individual variability in behavioral responses in various contexts and conditions, it is less appropriate to extrapolate behavioral effects as opposed to auditory responses. The available data on marine mammal behavioral responses to multiple pulse and nonpulse sounds are simply too variable and context-specific to justify proposing single disturbance criteria for broad categories of taxa and of sounds.

This should not, however, lead to the conclusion that there are insufficient data to conduct a systematic assessment of the likelihood that certain sound exposures will induce behavioral effects of variable seriousness in marine mammals. On the contrary, this field has seen many and accelerating strides in characterizing how certain kinds of sounds can affect marine mammal behavior. Quantification of the severity or significance of these effects will continue to be challenging. However, based on the NRC (2005) model described above in which behavioral reactions with a greater potential to affect vital rates are of particular concern, a simplistic scaling paradigm in which to consider the available data appears to provide the most justifiable way forward at present.

First, we developed an ordinal ranking of behavioral response severity (see Table 4). The intent of this scaling was to delineate those behaviors that are relatively minor and/or brief (scores 0-3); those with higher potential to affect foraging, reproduction, or survival (scores 4-6); and those considered likely to affect these vital rates (scores 7-9). This is an admittedly simplistic way of scaling the strikingly complex and poorly understood behavioral patterns of marine mammals in real-world conditions. It does provide a rudimentary framework for assessing the relative biological importance of behavioral responses and is likely a closer approximation of reality than previous step-function thresholds (as discussed in the "Historical Perspectives" section of Chapter 1). This approach emphasizes that "disturbance" is a graduated, rather than a "yes-or-no," phenomenon and that some noise-induced changes in behavior are more significant than others. We expect that future studies involving multivariate analysis of multiple behavioral response variables, multiple measures of acoustic exposure, and multiple contextual variables will provide a foundation for more sophisticated interpretations.

Second, we reviewed available research and observations for each of the five marine mammal functional hearing groups exposed to either multiple pulse or nonpulse sounds (i.e., Cells 2, 3, 5, 6, 8, 9, 11, 12, 14 & 15 in our matrix of sound type by animal group). We considered measurements of behavioral response both in the field and in the laboratory according to the behavioral severity scale. Studies with insufficient information on exposures and/or responses were considered but not included in the severity analysis. Where individual (and/or groups considered as an "individual"; see below) behavioral responses and associated received sound levels were reported, the observations were assigned the appropriate behavioral "score" from Table 4 and the case was included in a severity scoring table for the relevant matrix cell. One dimension in this type of table was the behavioral score (defined in Table 4); the other dimension was the received SPL within 10-dB ranges. Where multiple responses were reported for the same individual and/or group in a study (or where it was possible that this had been done—pseudoreplication), appropriate fractions of a single observation were assigned to relevant cells in the scoring table. As a result, there are fractional responses for some individual and/or group responses in the tabular severity-scaling forms. For example, a single behavioral observation for one individual was weighted as equivalent to ten observations for another individual by assigning each observation (some potentially in different RL/severity score bins) of the second individual a relative weight of 0.1.

Many observations of marine mammals involve multiple individuals because many species occur in large social groups and are followed as a group. In this case, if one individual responds to a sound, the other group members may respond to the response as opposed to the sound. In such observations, the full group was considered to represent an "individual" (i.e., the group became the unit of analysis). As a precautionary approach, the most severe response by any individual observed

Table 4. Severity scale for ranking observed behavioral responses of free-ranging marine mammals and laboratory subjects to various types of anthropogenic sound

Response score[1]	Corresponding behaviors (Free-ranging subjects)[2]	Corresponding behaviors (Laboratory subjects)[2]
0	- No observable response	- No observable response
1	- Brief orientation response (investigation/visual orientation)	- No observable response
2	- Moderate or multiple orientation behaviors - Brief or minor cessation/modification of vocal behavior - Brief or minor change in respiration rates	- No observable negative response; may approach sounds as a novel object
3	- Prolonged orientation behavior - Individual alert behavior - Minor changes in locomotion speed, direction, and/or dive profile but no avoidance of sound source - Moderate change in respiration rate - Minor cessation or modification of vocal behavior (duration < duration of source operation), including the Lombard Effect	- Minor changes in response to trained behaviors (e.g., delay in stationing, extended inter-trial intervals)
4	- Moderate changes in locomotion speed, direction, and/or dive profile but no avoidance of sound source - Brief, minor shift in group distribution - Moderate cessation or modification of vocal behavior (duration ≈ duration of source operation)	- Moderate changes in response to trained behaviors (e.g., reluctance to return to station, long inter-trial intervals)
5	- Extensive or prolonged changes in locomotion speed, direction, and/or dive profile but no avoidance of sound source - Moderate shift in group distribution - Change in inter-animal distance and/or group size (aggregation or separation) - Prolonged cessation or modification of vocal behavior (duration > duration of source operation)	- Severe and sustained changes in trained behaviors (e.g., breaking away from station during experimental sessions)
6	- Minor or moderate individual and/or group avoidance of sound source - Brief or minor separation of females and dependent offspring - Aggressive behavior related to noise exposure (e.g., tail/flipper slapping, fluke display, jaw clapping/gnashing teeth, abrupt directed movement, bubble clouds) - Extended cessation or modification of vocal behavior - Visible startle response - Brief cessation of reproductive behavior	- Refusal to initiate trained tasks
7	- Extensive or prolonged aggressive behavior - Moderate separation of females and dependent offspring - Clear anti-predator response - Severe and/or sustained avoidance of sound source - Moderate cessation of reproductive behavior	- Avoidance of experimental situation or retreat to refuge area (≤ duration of experiment) - Threatening or attacking the sound source
8	- Obvious aversion and/or progressive sensitization - Prolonged or significant separation of females and dependent offspring with disruption of acoustic reunion mechanisms - Long-term avoidance of area (> source operation) - Prolonged cessation of reproductive behavior	- Avoidance of or sensitization to experimental situation or retreat to refuge area (> duration of experiment)
9	- Outright panic, flight, stampede, attack of conspecifics, or stranding events - Avoidance behavior related to predator detection	- Total avoidance of sound exposure area and refusal to perform trained behaviors for greater than a day

[1] Ordinal scores of behavioral response severity are not necessarily equivalent for free-ranging vs laboratory conditions.

[2] Any single response results in the corresponding score (i.e., all group members and behavioral responses need not be observed). If multiple responses are observed, the one with the highest score is used for analysis.

within a group was used as the ranking for the whole group.

A specific category of behavioral studies was one in which marine mammal distributions were measured around a sound source during quiet and active periods. The available data typically involve comparisons of the distribution of animals before exposure ("control" or "reference") vs during exposure ("experimental"); the difference in distribution of the group was the behavioral response. Using this method, and given equivalent range measurements for control and experimental observations, "phantom" RLs for mammals detected during control periods (RLs that would have existed if in fact the source was active) can be calculated and compared to actual RLs during experimental conditions. In this way, the percentage of avoidance responses by individuals during the exposure was then calculated.

For the studies used in this analysis, noise exposure (including source and RL, frequency, duration, duty cycle, and other factors) was either directly reported or was reasonably estimated using simple sound propagation models deemed appropriate for the sources and operational environment. Because of the general lack of precision in many studies and the difficulties in pooling the results from disparate studies here, we pooled individual exposure SPL into 10-dB bins.

Our analysis of the available behavioral response studies presents raw, individual observations of reactions to multiple pulses and nonpulses as a function of exposure RL. The basic output of this procedure is a series of tables, one for each combination of the five marine mammal functional hearing groups and these two sound types (multiple pulses and nonpulses). The overall tally within each cell represents the number of individuals and/or independent group behavioral responses with estimated and/or measured RL in the specified 10-dB category.

This analysis is intended to provide some foundation for judging the degree to which available data suggest the existence of dose-response relationships between noise exposure and marine mammal behavior. An example of such a dose-response function is the Schultz (1978) curve used to predict growth of human annoyance with increasing noise level. The reader should note, however, that the substantial, acknowledged caveats and limitations of the current approach, particularly those related to contextual variables other than simply exposure level. Any application of the severity analyses given below should carefully consider the nature of the available information regarding sound source, species, sex/age class, sound-propagation environment, and especially the overall context of exposure relative to that shown in the studies reviewed here. The results from prior behavioral studies in which these variables are fairly similar to those in the anticipated exposure situation will very likely be the most relevant. Information from those studies should be most strongly weighted in assessing the likelihood of significant behavioral disturbance.

Criteria for Behavioral Disturbance: Single Pulse

For all cetaceans exposed to single pulses, the criteria were based on the Finneran et al. (2002b) results for TTS-onset in a beluga exposed to a single pulse. The unweighted peak sound pressure values of 224 dB re: 1 µPa (peak) and weighted (M_{mf}) SEL values of 183 dB re: 1 μPa^2-s are recommended as "behavioral" disturbance criteria for mid-frequency cetaceans (Table 5, Cell 4). By extrapolation (see cetacean procedure, Chapter 3, p. 439), the same values were also proposed for low- and high-frequency cetaceans (Table 5, Cells 1 & 7, respectively). The only difference in the application of these criteria to the three cetacean groups is the influence of the respective frequency-weighting functions for SEL criteria (M_{lf} and M_{hf} vs M_{mf}).

For pinnipeds exposed to single pulses in water, the proposed "behavioral" disturbance criteria are also the estimated TTS-onset values. For pinnipeds as a whole, these are 212 dB re: 1 µPa (peak) and weighted (M_{pw}) SEL of 171 dB re: 1 μPa^2-s (Table 5, Cell 10) as discussed in Chapter 3.

For pinnipeds in air, the proposed behavioral criteria are based on the strong responses (stampeding behavior that could injure some individuals or separate mothers from pups) of some species, especially harbor seals, to sonic booms from aircraft and missile launches in certain conditions (Berg et al., 2001, 2002; Holst et al., 2005a, 2005b). No responses resulting in injury were observed in these specific studies, but the behavioral responses were, in some cases, among those that would be considered relatively severe in regards to vital rates. It was therefore determined appropriate to use results from these studies rather than TTS-based thresholds for behavioral response criteria. The proposed criteria are 109 dB re: 20 µPa (peak) and frequency-weighted (M_{pa}) SEL of 100 dB re: (20 µPa)^2-s (Table 5, Cell 13). These levels are substantially below TTS-onset values. They are also probably quite precautionary as behavioral response criteria for the group as a whole, especially for species other than harbor seals where higher exposures were not observed to induce strong (or in some cases any) responses.

Table 5. Proposed behavioral response criteria for individual marine mammals exposed to various sound types; specific threshold levels are proposed for single pulses. See the referenced text sections and tables for severity scale analyses of behavioral responses to multiple pulses and nonpulses.

	Sound type		
Marine mammal group	Single pulses	Multiple pulses	Nonpulses
Low-frequency cetaceans	Cell 1	Cell 2[1]	Cell 3[6]
Sound pressure level	224 dB re: 1 μPa (peak) (flat)	Tables 6 & 7	Tables 14 & 15
Sound exposure level	183 dB re: 1 μPa^2-s (M_{lf})	Not applicable	Not applicable
Mid-frequency cetaceans	Cell 4	Cell 5[2]	Cell 6[7]
Sound pressure level	224 dB re: 1 μPa (peak) (flat)	Tables 8 & 9	Tables 16 & 17
Sound exposure level	183 dB re: 1 μPa^2-s (M_{mf})	Not applicable	Not applicable
High-frequency cetaceans	Cell 7	Cell 8[3]	Cell 9[8]
Sound pressure level	224 dB re: 1 μPa (peak) (flat)	[Tables 18 & 19]	Tables 18 & 19
Sound exposure level	183 dB re: 1 μPa^2-s (M_{hf})	Not applicable	Not applicable
Pinnipeds (in water)	Cell 10	Cell 11[4]	Cell 12[9]
Sound pressure level	212 dB re: 1 μPa (peak) (flat)	Tables 10 & 11	Tables 20 & 21
Sound exposure level	171 dB re: 1 μPa^2-s (M_{pw})	Not applicable	Not applicable
Pinnipeds (in air)	Cell 13	Cell 14[5]	Cell 15[10]
Sound pressure level	109 dB re: 20 μPa (peak) (flat)	Tables 12 & 13	Tables 22 & 23
Sound exposure level	100 dB re: (20 μPa)^2-s (M_{pa})	Not applicable	Not applicable

[1] "Low-Frequency Cetaceans/Multiple Pulses (Cell 2)" section
[2] "Mid-Frequency Cetaceans/Multiple Pulses (Cell 5)" section
[3] "High-Frequency Cetaceans/Multiple Pulses (Cell 8)" section
[4] "Pinnipeds in Water/Multiple Pulses (Cell 11)" section
[5] "Pinnipeds in Air/Multiple Pulses (Cell 14)" section
[6] "Low-Frequency Cetaceans/Nonpulses (Cell 3)" section
[7] "Mid-Frequency Cetaceans/Nonpulses (Cell 6)" section
[8] "High-Frequency Cetaceans/Nonpulses (Cell 9)" section
[9] "Pinnipeds in Water/Nonpulses (Cell 12)" section
[10] "Pinnipeds in Air/Nonpulses (Cell 15)" section

Behavioral Response Severity Scaling: Multiple Pulses

Low-Frequency Cetaceans/Multiple Pulses (Cell 2)
Numerous field observations have been made of low-frequency cetaceans reacting to multiple pulses either incidentally during ongoing operations or intentionally during experiments. A moderate number of species and experimental conditions have been considered, but the sources have usually been seismic airgun arrays. Some of the studies focused on migrating whales seen from fixed observation platforms or in/near migratory corridors. This approach minimizes pseudoreplication without the need for identifying individuals because individuals are unlikely to pass observers more than once.

Table 6 summarizes the methods used to obtain acoustic measurements and observations of behavioral or distributional responses (see Appendix B for more details). As in most cells, a number of reported observations were not scored or reported here due to lack of some key information and, in some cases, difficulties in accounting for various contextual variables. A few of these "excluded" studies are listed at the bottom of Table 6. Table 7 shows the results of the severity scaling analyses of individual and/or group responses, considering the studies deemed to contain sufficient data on exposure conditions and behavioral responses. For migrating bowhead whales, the onset of significant behavioral disturbance from multiple pulses occurred at RLs (RMS over pulse duration) around 120 dB re: 1 µPa (Richardson et al., 1999). For all other low-frequency cetaceans (including bowhead whales not engaged in migration), this onset was at RLs around 140 to 160 dB re: 1 µPa (Malme et al., 1983, 1984; Richardson et al., 1986; Ljungblad et al., 1988; Todd et al., 1996; McCauley et al., 1998, 2000) or perhaps higher (Miller et al., 2005). There is essentially no overlap in the RLs associated with onset of behavioral responses by members of these two groups based on the information currently available.

Mid-Frequency Cetaceans/Multiple Pulses (Cell 5)
A limited number of behavioral observations have been made of mid-frequency cetaceans exposed to

Table 6. Summary of behavioral responses by different species of low-frequency cetaceans exposed to multiple pulses (Cell 2) by type of sound source, available acoustic metrics, description of behavioral response (by individual and/or group), and a summary of corresponding severity score(s); where airgun array volume is stated, this is the total volume for all operating airguns in the array; 1 L = 61 in^3. Specific severity scores for each study are given in Table 7, and more details are given in Appendix B. Exposure RLs are given in dB SPL, which are RMS sound pressure levels (dB re: 1 µPa) over the duration of a pulse.

Study	Reference number (for Table 7)	Subject species	Sound source	Type of acoustic measurements	Type of individual and/or group behavioral responses	Study included in severity scale	Summary of severity scale analysis (see Table 7)
Malme et al. (1983)	1	Gray whales	Single airgun (1.64 L) & 20-gun 65.5-L airgun array	Calibrated RL measurements made *in situ* near areas of exposure	Land-based observations of individuals/groups; movement and respiration patterns during and without airguns	Yes	Exposure RLs 140-180 dB SPL; response severity scores: 0, 1, 3, 5 & 6
Malme et al. (1984)	2	Gray whales	Single airgun and airgun array	Calibrated RL measurements made *in situ* near areas of exposure	Land-based observations of individuals/groups; movement and respiration patterns during and without airguns	Yes	Exposure RLs 140-180 dB SPL; response severity scores: 0, 1, 3, 5 & 6
Richardson et al. (1986)	3	Bowhead whales (feeding)	Single airgun (0.66 L) and 30-gun 47-L array	Calibrated RL measurements made *in situ* near areas of exposure	Aerial observations of individuals/groups; movement and respiration patterns during and without airguns	Yes	Exposure RLs 140-180 dB SPL; response severity scores: 0, 1 & 6
Ljungblad et al. (1988)	4	Bowhead whales (feeding)	Single airgun (1.3 L) or 18- to 20-gun array	Calibrated RL measurements made *in situ* near areas of exposure	Aerial observations of individuals/groups; movement patterns and behavioral responses during and without airguns	Yes	Exposure RLs 140-180 dB SPL; response severity score: 6
Todd et al. (1996)	5	Humpback whales	Explosions	Limited to nominal measurements of explosives used (not measured on or near subjects)	Visual observations of whale behavior before and during use of explosives	Yes	Exposure RLs 150-160 dB SPL; response severity score: 3
McCauley et al. (1998)	6	Humpback whales (migrating)	Single airgun (0.33 L) and several arrays	Calibrated RL measurements made *in situ* near areas of exposure	Aerial and boat-based observations of individuals/groups; movement and behavioral patterns during and without airguns	Yes	Exposure RLs 150-170 dB SPL; response severity scores: 6 & 7
Richardson et al. (1999)	7	Bowhead whales (migrating)	Airgun array (6 to 16 guns; 9 to 25 L)	Calibrated RL measurements made *in situ* near areas of exposure	Aerial surveys of distribution of individuals/groups	Yes	Exposure RLs 110-140 dB SPL; response severity scores: 0, 1, 5 & 6
McCauley et al. (2000)	8	Humpback whales (socializing)	Single airgun (0.33 L)	Calibrated RL measurements made *in situ* near areas of exposure	Boat-based observations of individuals/groups; movement and behavioral patterns during and without airguns	Yes	Exposure RLs 140-180 dB SPL; response severity score: 6
Miller et al. (2005)	9	Bowhead whales (feeding)	Airgun array (24 guns; 36.9 L)	Calibrated RL measurements made *in situ* near areas of exposure	Vessel-based observations of individuals; aerial surveys of distribution; movement/diving patterns and behavioral responses during and without airguns	Yes	Exposure RLs 140-180 dB SPL; response severity scores: 0 & 6
Reeves et al. (1984)	Not included	Bowhead whales (migrating)	Seismic airgun array	Insufficient data for this analysis	Insufficient data for this analysis	No	N/A
Malme et al. (1985)	Not included	Humpback whales	Seismic airgun array	Insufficient data for this analysis	Insufficient data for this analysis	No	N/A
Malme et al. (1986, 1988)	Not included	Gray whales	Single airgun and airgun array	Insufficient data for this analysis	Insufficient data for this analysis	No	N/A
Koski & Johnson (1987)	Not included	Bowhead whales (migrating)	Seismic airgun	Insufficient data for this analysis	Insufficient data for this analysis	No	N/A

Table 7. Number (in **bold**) of low-frequency cetaceans (individuals and/or groups) reported as having behavioral responses to multiple pulse noise; responses were categorized into 10-dB RL bins, ranked by severity of the behavioral response (see Table 4 for severity scaling), and combined with other observations having the same RL/severity score. A summary of the individual studies included in this table is given in the "Low-Frequency Cetaceans/Multiple Pulses (Cell 2)" section of this chapter. Parenthetical subscripts indicate the reference reporting the observations as listed in Table 6.

	Received RMS sound pressure level (dB re: 1 μPa)											
Response score	80 to < 90	90 to < 100	100 to < 110	110 to < 120	120 to < 130	130 to < 140	140 to < 150	150 to < 160	160 to < 170	170 to < 180	180 to < 190	190 to < 200
9												
8												
7								**1.0** $_{(6)}$				
6				**9.5** $_{(7)}$	**47.4** $_{(7)}$	**2.2** $_{(7)}$	**3.4** $_{(4, 6, 8)}$	**5.8** $_{(1, 2, 3, 6)}$	**4.5** $_{(1, 2, 3, 4, 6)}$	**8.3** $_{(1, 2, 4, 8, 9)}$		
5					**1.0** $_{(7)}$		**1.0** $_{(4)}$	**1.0** $_{(1, 2)}$				
4												
3									**1.0** $_{(1, 2)}$	**1.0** $_{(1, 2)}$		
2												
1				**5.0** $_{(7)}$	**6.0** $_{(7)}$	**1.0** $_{(7)}$	**2.5** $_{(1, 2, 3)}$	**3.0** $_{(5)}$				
0				**59.8** $_{(7)}$	**17.7** $_{(7)}$	**1.1** $_{(7, 9)}$	**0.1** $_{(9)}$	**0.6** $_{(3, 9)}$	**6.8** $_{(1, 2, 3, 9)}$	**6.3** $_{(1, 2, 9)}$		

multiple pulses. Field observations have involved sperm whales and a few other odontocete species exposed to seismic airguns and explosives. Laboratory investigations have considered behavioral responses to various kinds of multiple pulse sources. Again, some observations were excluded due to lack of relevant information. Four studies of individual mid-frequency cetacean responses to multiple pulse exposures contained sufficient acoustic and behavioral information for inclusion in this analysis. These include field observations of free-ranging sperm whales and belugas studied by Madsen & Møhl (2000), Madsen et al. (2002), and Miller et al. (2005), as well as laboratory observations of captive false killer whales by Akamatsu et al. (1993). The information from these studies is summarized in Table 8 and discussed in detail in Appendix B; the companion severity scaling analysis is shown in Table 9.

The combined data for mid-frequency cetaceans exposed to multiple pulses do not indicate a clear tendency for increasing probability and severity of response with increasing RL. In certain conditions, multiple pulses at relatively low RLs (~80 to 90 dB re: 1 μPa) temporarily silence individual vocal behavior for one species (sperm whales). In other cases with slightly different stimuli, RLs in the 120 to 180 dB re: 1 μPa range failed to elicit observable reaction from a significant percentage of individuals either in the field or in the laboratory.

High-Frequency Cetaceans/Multiple Pulses (Cell 8)

Based on our source type distinction (see Chapter 2), virtually all sources of transient sound used in quantitative behavioral studies of high-frequency cetaceans—for example, acoustic harassment devices (AHDs) and acoustic deterrent devices (ADDs)—would be characterized as nonpulse sounds. While individual elements produced by some of these sources could be characterized as pulses, and sequences of them as multiple pulses, they are generally emitted in such rapid fashion that some mammalian auditory systems likely perceive them as nonpulses. Further, some AHDs and ADDs, and most other sources used in behavioral studies with high-frequency cetaceans, lack the characteristics of pulses such as extremely fast rise-time, correspondingly broad frequency bandwidth, and high kurtosis. Due to uncertainty over the extent to which some of these signals may be perceived and the overarching paucity of data, it is not possible to present any data on behavioral responses of high-frequency cetaceans as a function of received levels of multiple pulses. Available data for nonpulse sounds are considered below (see the "High-Frequency Cetaceans/Nonpulses [Cell 9]" section). We note the need for empirical behavioral research in these animals using sound sources (such as airgun or pile-driving stimuli) unequivocally classified as multiple pulses (see Chapter 5).

Table 8. Summary of behavioral responses by different species of mid-frequency cetaceans exposed to multiple pulses (Cell 5) by type of sound source, available acoustic metrics, description of behavioral response (by individual and/or group), and a summary of corresponding severity score(s); specific severity scores for each study are given in Table 9 and more details are given in Appendix B. Exposure RLs are given in dB SPL, which are RMS sound pressure levels (dB re: 1 µPa) over the duration of a pulse.

Study	Reference number (for Table 9)	Subject species	Sound source	Type of acoustic measurements	Type of individual and/or group behavioral responses	Study included in severity scale	Summary of severity scale analysis (see Table 9)
Madsen & Møhl (2000)	1	Sperm whales	Small explosives (several per day)	Calibrated RL measurements made *in situ* near areas of exposure	Vessel-based observations of individuals, including visual detection and passive acoustic monitoring of vocalizations	Yes	Exposure RLs 170-180 dB SPL; response severity score: 0
Madsen et al. (2002)	2	Sperm whales	Airgun array (distant)	Calibrated RL measurements made *in situ* near areas of exposure	Vessel-based observations of individuals, including visual detection and passive acoustic monitoring of vocalizations	Yes	Exposure RLs 120-140 dB SPL; response severity score: 0
Miller et al. (2005)	3	Beluga	Airgun array (24 guns; 36.9 L)	Calibrated RL measurements made *in situ* near areas of exposure	Vessel-based observations of individuals; aerial surveys of distribution; movement/diving patterns and behavioral responses during and without airguns	Yes	Exposure RLs 100-150 dB SPL; response severity scores: 0 & 6
Akamatsu et al. (1993)	4	False killer whales (captive)	Numerous sounds, including pulse sequences	Calibrated RL measurements made *in situ* within experimental enclosure	Visual observations of behavioral responses within experimental context in laboratory conditions	Yes	Exposure RLs 170-180 dB SPL; response severity scores: 0 & 6
André et al. (1997)	Not included	Sperm whales	Natural and artificial pulses (repeated)	Insufficient data for this analysis	Vessel-based observations of individuals; diving patterns and vocal behavior	No	N/A
Stone (2003)	Not included	Several mid-freq. cetacean species	Seismic airgun arrays (various)	Insufficient data for this analysis	Vessel-based observations of individuals; sightings data and avoidance behavior	No	N/A

Table 9. Number (in **bold**) of mid-frequency cetaceans (individuals and/or groups) reported as having behavioral responses to multiple pulse noise; responses were categorized into 10-dB RL bins, ranked by severity of the behavioral response (see Table 4 for severity scaling), and combined with other observations having the same RL/severity score. A summary of the individual studies included in this table is given in the "Mid-Frequency Cetaceans/Multiple Pulses (Cell 5)" section of this chapter. Parenthetical subscripts indicate the reference reporting the observations as listed in Table 8.

	Received RMS sound pressure level (dB re: 1 µPa)											
Response score	80 to < 90	90 to < 100	100 to < 110	110 to < 120	120 to < 130	130 to < 140	140 to < 150	150 to < 160	160 to < 170	170 to < 180	180 to < 190	190 to < 200+
9												
8												
7												
6					**0.17** (3)	**0.17** (3)	**0.17** (3)			**1.3** (4)		
5												
4												
3												
2												
1												
0			**0.25** (3)	**0.25** (3)	**3.0** (2)	**4.0** (2)				**6.7** (1, 4)		

Pinnipeds in Water/Multiple Pulses (Cell 11)

Information on behavioral reactions of pinnipeds in water to multiple pulses involves exposures to small explosives used in fisheries interactions, impact pile driving, and seismic surveys. Several studies lacked matched data on acoustic exposures and behavioral responses by individuals. As a result, the quantitative information on reactions of pinnipeds in water to multiple pulses is very limited (see Table 10). The severity scaling analysis for individual behavioral responses for Cell 11 is given in Table 11.

Our general finding is that, based on the limited data on pinnipeds in water exposed to multiple pulses, exposures in the ~150 to 180 dB re: 1 µPa range (RMS values over the pulse duration) generally have limited potential to induce avoidance behavior in pinnipeds. RLs exceeding 190 dB re: 1 µPa are likely to elicit responses, at least in some ringed seals (Harris et al., 2001; Blackwell et al., 2004b; Miller et al., 2005). Note that the SEL associated with a single 190 dB re: 1 µPa (RMS) pulse from an airgun is typically *ca.* 175 dB re: 1 µPa^2-s. That exceeds the estimated TTS threshold for the closely related harbor seal (171 dB re: 1 µPa^2-s; see Chapter 3). Thus, in the case of ringed seals exposed to sequences of airgun pulses from an approaching seismic vessel, most animals may show little avoidance unless the RL is high enough for mild TTS to be likely.

Pinnipeds in Air/Multiple Pulses (Cell 14)

How multiple pulses produced in air affect pinnipeds was among the least well-documented of the conditions we considered. Most of the available data on responses to pulses were from single pulse events (e.g., rocket launches) over populations of pinnipeds exposed to such signals repeatedly (e.g., Thorson et al., 1998, 1999, 2000a, 2000b; Berg et al., 2001, 2002, 2004). These events do not occur frequently enough for the exposures to be considered multiple pulses, and many of them contained nonpulse as well as pulse exposures. They are discussed in some detail in Appendix B (as well as in Appendix C when nonpulses are involved). Appendix B also discusses several other studies potentially relevant to Cell 14 but ultimately not used in this analysis. Consequently, the quantitative information analyzed for reactions of pinnipeds in air exposed to multiple pulses (see Tables 12 & 13) focused on the aerial data by Blackwell et al. (2004b). These extremely limited data suggest very minor, if any, observable behavioral responses by pinnipeds exposed to airborne pulses with RLs 60 to 80 dB re: 20 µPa.

Behavioral Response Severity Scaling: Nonpulses

Low-Frequency Cetaceans/Nonpulses (Cell 3)

While there are clearly major areas of uncertainty remaining, there has been relatively extensive behavioral observation of low-frequency cetaceans exposed to nonpulse sources. As summarized in Table 14 (and discussed in greater detail in Appendix C), these field observations involve the majority of low-frequency cetacean species exposed to a wide range of industrial, active sonar, and tomographic research active sources (Baker et al., 1982; Malme et al., 1983, 1984, 1986;

Table 10. Summary of behavioral responses by different species of pinnipeds in water exposed to multiple pulses (Cell 11) by type of sound source, available acoustic metrics, description of behavioral response (by individual and/or group), and a summary of corresponding severity score(s); specific severity scores for each study are given in Table 11 and more details are given in Appendix B. Exposure RLs are given in dB SPL, which are RMS sound pressure levels (dB re: 1 µPa) over the duration of a pulse.

Study	Reference number (for Table 11)	Subject species	Sound source	Type of acoustic measurements	Type of individual and/or group behavioral responses	Study included in severity scale	Summary of severity scale analysis (see Table 11)
Harris et al. (2001)	1	Ringed (mainly), bearded, and spotted seals	Single airgun and 11-gun, 21.6-L array	RLs measured *in situ* near individuals observed in defined spatial zones	Vessel-based observations of individuals within specified zones over a limited range	Yes	Exposure RLs 160-200 dB SPL; response severity scores: 0 & 6
Blackwell et al. (2004b)	2	Ringed seals	Pipe-driving sounds (construction)	RLs measured *in situ* near individuals observed (detailed measurements, including peak pressure, RMS, SEL, and duration)	Land-based observations of individuals; movement and response patterns during pipe-driving (note that construction activities had been underway for a considerable period before observations)	Yes	Exposure RLs 150-160 dB SPL; response severity scores: 0 & 1
Miller et al. (2005)	3	Ringed and bearded seals	Airgun array (24 airguns; 36.9 L)	Calibrated RL measurements made *in situ* near areas of exposure	Vessel-based observations of individuals; movement patterns and behavioral responses during and without airguns	Yes	Exposure RLs 170-200 dB SPL; response severity score: 0
Shaughnessy et al. (1981)	Not included	California sea lions	Seal bombs (small explosives)	Insufficient data for this analysis	Visual observations of individual responses over multiple exposures	No	N/A
Mate & Harvey (1987)	Not included	California sea lions	Seal bombs (small explosives)	Insufficient data for this analysis	Visual observations of individual responses over multiple exposures	No	N/A
Moulton et al. (2003, 2005)	Not included	Ringed seals		Calibrated measurements made in the area of exposure	Complicated by simultaneous exposure to pulse and nonpulse sources	No	N/A

Table 11. Number (in **bold**) of pinnipeds in water (individuals and/or groups) reported as having behavioral responses to multiple pulse noise. Responses were categorized into 10-dB RL bins, ranked by severity of the behavioral response (see Table 4 for severity scaling), and combined with other observations having the same RL/severity score; a summary of the individual studies included in this table is given in the "Pinnipeds in Water/Multiple Pulses (Cell 11)" section of this chapter. Parenthetical subscripts indicate the reference reporting the observations as listed in Table 10.

	Received RMS sound pressure level (dB re: 1 µPa)											
Response score	80 to < 90	90 to < 100	100 to < 110	110 to < 120	120 to < 130	130 to < 140	140 to < 150	150 to < 160	160 to < 170	170 to < 180	180 to < 190	190 to < 200
9												
8												
7												
6									**1.7** $_{(1)}$	**2.1** $_{(1)}$		**45.4** $_{(1)}$
5												
4												
3												
2												
1						**0.3** $_{(2)}$						
0								**0.7** $_{(2)}$	**5.3** $_{(1)}$	**30.3** $_{(1, 3)}$	**0.3** $_{(3)}$	**9.9** $_{(1, 3)}$

Richardson et al., 1990b; McCauley et al., 1996; Biassoni et al., 2000; Croll et al., 2001; Palka & Hammond, 2001; Nowacek et al., 2004).

The combined information generally indicates no (or very limited) responses at RLs 90 to 120 dB re: 1 µPa and an increasing probability of avoidance and other behavioral effects in the 120 to 160 dB re: 1 µPa range (severity scaling: Table 15). However, these data also indicated considerable variability in RLs associated with behavioral responses. Contextual variables (e.g., source proximity, novelty, operational features) appear to have been at least as important as exposure level in predicting response type and magnitude.

Mid-Frequency Cetaceans/Nonpulses (Cell 6)

A relatively large number of mid-frequency cetaceans have been observed in the field and in the laboratory responding to nonpulse sounds, including vessels and watercraft (LGL & Greeneridge, 1986; Gordon et al., 1992; Palka & Hammond, 2001; Buckstaff, 2004; Morisaka et al., 2005), pulsed pingers and AHDs/ADDs (Watkins & Schevill, 1975; Morton & Symonds, 2002; Monteiro-Neto et al., 2004), industrial activities (Awbrey & Stewart, 1983; Richardson et al., 1990b), mid-frequency active sonar (NRL, 2004a, 2004b; NMFS, 2005), and tones or bands of noise in laboratory conditions (Nachtigall et al., 2003; Finneran & Schlundt, 2004). Summary information on these studies is given in Table 16; detailed descriptions are given in Appendix C. As in other conditions, a number of potentially relevant field studies are not included in the severity scaling analysis due to lack of sufficiently detailed information.

An additional challenge in interpreting many of the field data for this condition is isolating the effect of RL from the effects of mere source presence (as possibly indicated by visual stimuli or other aspects of acoustic exposure such as the presence of high-frequency components) and other contextual variables. For this reason, several studies were considered but not integrated into the analysis. The laboratory observations are of captive cetaceans exposed to precisely controlled and known noise exposures in the context of hearing and TTS experiments. However, the relevance of behavioral reactions of trained, food-reinforced captive animals exposed to noise to the reactions of free-ranging marine mammals is debatable. This is discussed in greater detail in Appendix C.

The combined field and laboratory data for mid-frequency cetaceans exposed to nonpulse sounds do not lead to a clear conclusion about RLs coincident with various behavioral responses (see severity scaling, Table 17). In some settings, individuals in the field showed behavioral responses with high severity scores to exposures from 90 to 120 dB re: 1 µPa, while others failed to exhibit such responses for exposure RLs from 120 to 150 dB re: 1 µPa. Contextual variables other than exposure RL, and probable species differences, are the likely reasons for this variability in response. Context may also explain why there is great disparity in results from field and laboratory conditions—exposures in captive settings generally exceeded 170 dB re: 1 µPa before inducing behavioral responses.

Table 12. Summary of behavioral responses by different species of pinnipeds in air exposed to multiple pulses (Cell 14) by type of sound source, available acoustic metrics, description of behavioral response (by individual and/or group), and a summary of corresponding severity score(s); specific severity scores for each study are given in Table 13 and more details are given in Appendix B. Exposure RLs are given in dB SPL, which are RMS sound pressure levels (dB re: 20 µPa) over the duration of a pulse.

Study	Reference number (for Table 13)	Subject species	Sound source	Type of acoustic measurements	Type of individual and/or group behavioral responses	Study included in severity scale	Summary of severity scale analysis (see Table 13)
Blackwell et al. (2004b)	1	Ringed seals	Pipe-driving sounds (construction)	RLs measured *in situ* near individuals observed (detailed measurements, including peak pressure, RMS, SEL, and duration)	Land-based observations of individuals; movement and response patterns during pipe-driving (note that construction activities had been underway for a considerable period before observations)	Yes	Exposure RLs 60-80 dB SPL re: 20 µPa; response severity scores: 0 & 1
Perry et al. (2002)	Not included	Harbor and gray seals	Repeated sonic booms	Measured sound overpressure levels on breeding beaches, but not RLs at positions of exposed animals	Land-based observations of animal presence, behavior, and heart rate (note long history of sonic booms in the area)	No	N/A

Table 13. Number (in **bold**) of pinnipeds in air (individuals and/or groups) reported as having behavioral responses to multiple pulse noise; responses were categorized into 10-dB RL bins, ranked by severity of the behavioral response (see Table 4 for severity scaling), and combined with other observations having the same RL/severity score. A summary of the individual studies included in this table is given in the "Pinnipeds in Air/Multiple Pulses (Cell 14)" section of this chapter. Parenthetical subscripts indicate the reference reporting the observations as listed in Table 12.

	Received RMS sound pressure level (dB re: 20 µPa)						
Response score	50 to < 60	60 to < 70	70 to < 80	80 to < 90	90 to < 100	100 to < 110	110 to < 120
9							
8							
7							
6							
5							
4							
3							
2							
1		**0.125** $_{(1)}$					
0		**0.625** $_{(1)}$	**0.25** $_{(1)}$				

High-Frequency Cetaceans/Nonpulses (Cell 9)

Numerous controlled studies have been conducted on the behavioral reactions of high-frequency cetaceans to various nonpulse sound sources both in the field (Culik et al., 2001; Olesiuk et al., 2002; Johnston, 2002) and in laboratory settings (Kastelein et al., 1997, 2000, 2005, 2006a). However, only one high-frequency species (harbor porpoise) has been extensively studied and that species provided all the available data on behavioral response magnitude vs received exposure conditions. The original studies were attempts to reduce harbor porpoise bycatch by attaching warning pingers to fishing gear. More recent studies consider whether AHDs and ADDs also exclude harbor porpoises from critical habitat areas, and whether these devices affect harbor porpoise behavior in controlled laboratory conditions.

The combined wild and captive animal data (summarized in Table 18 and discussed in detail in Appendix C) clearly support the observation that harbor porpoises are quite sensitive to a wide range of human sounds at very low exposure RLs (~90 to 120 dB re: 1 µPa), at least for initial exposures. This observation is also evident in the severity scaling analysis for Cell 9 (Table 19). All recorded exposures exceeding 140 dB re: 1 µPa induced profound and sustained avoidance behavior in wild harbor porpoises. Whether this apparently high degree of behavioral sensitivity to anthropogenic acoustic sources extends to other high-frequency cetacean species (or nonpulse sources other than AHDs and ADDs) is unknown. Given the lack of information to the contrary, however, such a relationship should be assumed as a precautionary measure. Habituation to sound exposure was noted in some but not all studies. Strong initial reactions of high-frequency cetaceans at relatively low levels may in some conditions wane with repeated exposure and subject experience.

Pinnipeds in Water/Nonpulses (Cell 12)

The effects of nonpulse exposures on pinnipeds in water are poorly understood. Studies for which enough information was available for analysis include field exposures of harbor seals to AHDs (Jacobs & Terhune, 2002) and exposure of translocated freely diving northern elephant seals to a research tomography source (Costa et al., 2003), as well as responses of captive harbor seals to underwater data communication sources (Kastelein et al., 2006b). These limited available data (see Table 20 & Appendix C) suggested that exposures between ~90 and 140 dB re: 1 µPa generally do not appear to induce strong behavioral responses in pinnipeds exposed to nonpulse sounds in water; no data exist regarding exposures at higher levels. The severity scale results for Cell 12 are given in Table 21.

It is important to note that among these studies of pinnipeds responding to nonpulse exposures in water, there are some apparent differences in responses between field and laboratory conditions. Specifically, in this case, captive subjects responded more strongly at lower levels than did animals in the field. Again, contextual issues are the likely cause of this difference. Captive subjects in the Kastelein et al. (2006b) study were not reinforced with food for remaining in noise fields, in contrast to the laboratory studies for mid-frequency cetaceans described above. Subjects in the

Table 14. Summary of behavioral responses by different species of low-frequency cetaceans exposed to nonpulses (Cell 3) by type of sound source, available acoustic metrics, description of behavioral response (by individual and/or group), and a summary of corresponding severity score(s); specific severity scores for each study are given in Table 15 and more details are given in Appendix C. Exposure RLs are given in dB SPL, which are RMS sound pressure levels (dB re: 1 µPa).

Study	Reference number (for Table 15)	Subject species	Sound source	Type of acoustic measurements	Type of individual and/or group behavioral responses	Study included in severity scale	Summary of severity scale analysis (see Table 15)
Baker et al. (1982)	1	Humpback whales	Vessel noise and presence	Individual RLs not reported but vessels identical to previous measurements	Vessel-based observations of individual movement and behavioral patterns around vessels	Yes	Exposure RLs 100-140 dB SPL; severity scores: 0 & 6
Malme et al. (1983, 1984)	2	Gray whales (migrating)	Playbacks of drilling and machinery noise	RLs measured *in situ* near individuals observed	Shore-based observations of individual movement and behavioral patterns around simulated drilling operations/platforms	Yes	Exposure RLs 90-150 dB SPL; severity scores: 0 & 6
Malme et al. (1986)	3	Gray whales (feeding)	Playbacks of drilling noise	RLs measured *in situ* near individuals observed	Vessel-based observations of individual movement and behavioral patterns before and during playbacks	Yes	Exposure RLs 100-120 dB SPL; severity scores: 0 & 6
Richardson et al. (1990b)	4	Bowhead whales (migrating)	Drilling noise playbacks	Detailed and calibrated source and transmission loss measurements allowed good RL estimates	Visual observations of individual movement and behavioral patterns before, during, and after exposure to drilling sounds	Yes	Exposure RLs 100-140 dB SPL; severity scores: 0 & 6
McCauley et al. (1996)	5	Humpback whales	Vessel noise and presence	RLs measured *in situ* near individuals observed	Visual observations of individual movement and behavioral patterns during vessel approaches	Yes	Exposure RLs 110-130 dB SPL; severity score: 6
Frankel & Clark (1998)	6	Humpback whales	Low-frequency M-sequence playback	Calibrated RL measurements made *in situ* near areas of exposure	Visual observations of individual movement and behavioral patterns before, during, and after playbacks	Yes	Exposure RLs 120-130 dB SPL; severity score: 6
Biassoni et al. (2000); Miller et al. (2000)	7	Humpback whales	Low-frequency sonar playback	Calibrated RL measurements made *in situ* near areas of exposure	Visual observations of individual movement and behavioral patterns before, during, and after playbacks	Yes	Exposure RLs 110-160 dB SPL; severity scores: 2 & 4
Croll et al. (2001)	8	Blue and fin whales (feeding)	Low-frequency sonar playback	Calibrated RL measurements and modeling for area of exposure	Individual responses not reported but a general observation of feeding behavior with/without sonar	Yes	Exposure RLs 140-150 dB SPL; severity score: 0

Table 14 (continued)

Study	Reference number (for Table 15)	Subject species	Sound source	Type of acoustic measurements	Type of individual and/or group behavioral responses	Study included in severity scale	Summary of severity scale analysis (see Table 15)
Palka & Hammond (2001)	9	Minke whales	Vessel noise and presence	RL estimates based on source and environmental characteristics	Visual observations of individual and group movements and behavioral patterns during vessel approaches	Yes	Exposure RLs 110-120 dB SPL; severity score: 3
Nowacek et al. (2004)	10	Right whales	Playbacks of several nonpulses	Subjects wore calibrated tags that measured RL and behavior/movement	Detailed measurements of vocal and physical reactions of animals before, during, and after playbacks	Yes	Exposure RLs 120-150 dB SPL; severity scores: 0 & 7
Dahlheim (1987)	Not included	Gray whales	Playbacks of nonpulses	Insufficient data for this analysis	Visual and acoustic observations of individuals	No	N/A
Borggaard et al. (1999)	Not included	Various cetaceans	Industrial noise	Some RL measurements and modeling in area	Insufficient data on individual responses for this analysis	No	N/A
Frankel & Clark (2000)	Not included	Humpback whales	ATOC source	Some RL measurements and modeling in area	Insufficient data on individual responses for this analysis	No	N/A
Schick & Urban (2000)	Not included	Bowhead whales	Drillships	Insufficient data for this analysis	Visual observations of individuals around rigs	No	N/A
Frankel & Clark (2002)	Not included	Humpback whales	ATOC source	Some RL measurements and modeling in area	Insufficient data on individual responses for this analysis	No	N/A
Jahoda et al. (2003)	Not included	Fin whales	Vessel noise and presence	Insufficient data for this analysis	Visual observations of individuals during approaches	No	N/A
Mobley (2005)	Not included	Humpback whales	ATOC source	Some RL measurements and modeling in area	Insufficient data on individual responses for this analysis	No	N/A

Table 15. Number (in **bold**) of low-frequency cetaceans (individuals and/or groups) reported as having behavioral responses to nonpulses; responses were categorized into 10-dB RL bins, ranked by severity of the behavioral response (see Table 4 for severity scaling), and combined with other observations having the same RL/severity score. A summary of the individual studies included in this table is given in the "Low-Frequency Cetaceans/Nonpulses (Cell 3)" section of this chapter. Parenthetical subscripts indicate the reference reporting the observations as listed in Table 14.

	Received RMS sound pressure level (dB re: 1 µPa)											
Response score	80 to < 90	90 to < 100	100 to < 110	110 to < 120	120 to < 130	130 to < 140	140 to < 150	150 to < 160	160 to < 170	170 to < 180	180 to < 190	190 to < 200
9												
8												
7						**2.5**$_{(10)}$	**1.5**$_{(10)}$					
6		**4.9**$_{(2)}$	**7.4**$_{(1, 2, 4)}$	**16.2**$_{(1, 2, 3, 5)}$	**13.6**$_{(2, 5)}$	**4.2**$_{(1, 2)}$	**0.8**$_{(2)}$					
5												
4				**3.0**$_{(5, 7)}$	**1.0**$_{(7)}$		**1.0**$_{(7)}$					
3			**1,117**$_{(9)}$	**0.27**$_{(6)}$								
2			**0.5**$_{(7)}$	**4.0**$_{(7)}$	**5.0**$_{(7)}$	**2.0**$_{(7)}$	**1.0**$_{(7)}$					
1												
0	**1.1**$_{(2)}$	**82.6**$_{(2, 3, 4)}$	**33.9**$_{(1, 2, 3, 4)}$	**7.08**$_{(2, 4, 6, 10)}$	**7.2**$_{(4, 10)}$	**1.45**$_{(2, 8, 10)}$						

field may have been more tolerant of exposures because of motivation to return to a safe location (Costa et al., 2003) or motivation to approach enclosures holding prey items (Jacobs & Terhune, 2002).

Pinnipeds in Air/Nonpulses (Cell 15)

There has been considerable effort to study the effects of aerial nonpulse sounds on pinniped behavior, primarily involving rocket launches, aircraft overflights, powerboat approaches, and construction noise. Unfortunately, as discussed in Appendix C, many of the studies are difficult to interpret in terms of exposure RL and individual or group behavioral responses. In many cases, it was difficult or impossible to discern whether the reported behavioral response was induced by the noise from a specific operation or some correlated variable such as its visual presence. For these reasons, most of the observational studies of behavioral disturbance were not appropriate for scoring behavioral responses relative to exposure RL. However, a number of the technical reports and analyses of rocket launches are relevant for this cell and contain sufficiently detailed information regarding estimated RLs. These observations are, however, complicated by the fact that all studies were conducted in the same general area with subjects likely habituated to the presence of launch noise. Further, in many cases, exposures contained both a nonpulse component and a pulse component (described below). Only those observations (Thorson et al., 1999, 2000b; Berg et al., 2002) for which there was clearly just nonpulse exposure were considered in the severity scaling analyses for this condition.

The limitations of these and other potentially applicable studies resulted in a very limited data set for use in this analysis (see summary in Table 22 and severity scaling analysis in Table 23). As a general statement from the available information, pinnipeds exposed to intense (~110 to 120 dB re: 20 µPa) nonpulse sounds tended to leave haulout areas and seek refuge temporarily (minutes to a few hours) in the water, whereas pinnipeds exposed to distant launches at RLs ~60 to 70 dB re: 20 µPa tended to ignore the noise. It is difficult to assess the relevance of either of these observations to naïve individuals, however, given the repeated exposure of study colonies to such noise events and the potential that observed individuals were habituated. Due to the limitations of available data, it is not currently possible to make any further general characterizations regarding this condition.

Table 16. Summary of behavioral responses by different species of mid-frequency cetaceans exposed to nonpulses (Cell 6) by type of sound source, available acoustic metrics, description of behavioral response (by individual and/or group), and a summary of corresponding severity score(s); specific severity scores for each study are given in Table 17 and more details are given in Appendix C. Exposure RLs are given in dB SPL, which are RMS sound pressure levels (dB re: 1 μPa).

Study	Reference number (for Table 17)	Subject species	Sound source	Type of acoustic measurements	Type of individual and/or group behavioral responses	Study included in severity scale	Summary of severity scale analysis (see Table 17)
Watkins & Schevill (1975)	1	Sperm whales	Pingers	RLs measured *in situ* near individuals observed	Passive acoustic monitoring of vocal output of individuals during exposure	Yes	Exposure RLs 80-90 dB SPL; severity score: 3
Awbrey & Stewart (1983)	2	Belugas	Playbacks of drilling sounds	RL estimates based on source and environmental characteristics	Visual observations of individual and group movements and behavioral patterns during exposure and control trials	Yes	Exposure RLs 110-150 dB SPL; severity scores: 0, 1, 2 & 6
LGL & Greeneridge (1986)	3	Belugas and narwhals	Ship and ice-breaking noise	Calibrated RL measurements made *in situ* near areas of exposure	Ice-based and aerial observations of groups of animals; movement and behavioral patterns before, during, and after ice-breaking	Yes	Exposure RLs 90-120 dB SPL; severity scores: 0, 1, 2, 3 & 8
Richardson et al. (1990b)	4	Belugas	Playbacks of drilling sounds	RL estimates based on source and environmental characteristics plus sonobuoy data	Ice-based and aerial observations of individual and group movements and behavior during exposure and control trials	Yes	Exposure RLs 100-130 dB SPL; severity scores: 0, 1, 3 & 4
Gordon et al. (1992)	5	Sperm whales	Vessel noise and presence	Calibrated RL measurements made *in situ* near areas of exposure	Vessel-based observations and passive acoustic monitoring of individuals; movement patterns and behavioral responses	Yes	Exposure RLs 110-120 dB SPL; severity score: 3
Palka & Hammond (2001)	6	White-sided and white-beaked dolphins	Vessel noise and presence	RL estimates based on source and environmental characteristics	Visual observations of individual and group movements and behavioral patterns during vessel approaches	Yes	Exposure RLs 110-120 dB SPL; severity score: 3
Morton & Symonds (2002)	7	Killer whales	Various AHDs	RL estimates based on source and environmental characteristics	Census data for individual and group sightings used to estimate "exclusion" zones	Yes	Exposure RLs 140-150 dB SPL; severity score: 8
Buckstaff (2004)	8	Bottlenose dolphins	Vessel noise and presence (approaches)	Calibrated RL measurements made *in situ* near areas of exposure	Passive acoustic monitoring of individual vocal output during vessel approaches	Yes	Exposure RLs 110-120 dB SPL; severity score: 2
NRL (2004a, 2004b); NMFS (2005)	9	Killer whales	Mid-frequency active military sonar	Some calibrated RL measurements and RL estimates from modeling source and environmental characteristics	Visual observations of individual and group movements and behavioral patterns before, during, and after incidental exposure	Yes	Exposure RLs 160-170 dB SPL; severity score: 6

Table 16 (continued)

Study	Reference number (for Table 17)	Subject species	Sound source	Type of acoustic measurements	Type of individual and/or group behavioral responses	Study included in severity scale	Summary of severity scale analysis (see Table 17)
Monteiro-Neto et al. (2004)	10	Tucuxi (river dolphins)	Dukane® Netmark ADDs	RL estimates based on source and environmental characteristics	Visual observations of individual and group movements and behavioral patterns during exposure and control trials	Yes	Exposure RLs 110-120 dB SPL; severity score: 6
Morisaka et al. (2005)	11	Indo-Pacific dolphins	Vessel noise and presence	Calibrated RL measurements made *in situ* near areas of exposure	Passive acoustic monitoring of individual vocal output during vessel approaches	Yes	Exposure RLs 120-130 dB SPL; severity score: 5
Nachtigall et al. (2003)	12	Bottlenose dolphins (captive)	Nonpulse noise (bands)	Calibrated RL measurements *in situ* within test enclosure	Visual observations of behavioral responses within experimental lab context	Yes	Exposure RLs 170-180 dB SPL; severity score: 6
Finneran & Schlundt (2004)	13	Bottlenose dolphins (captive)	Nonpulse noise (tones)	Calibrated RL measurements made *in situ* within test enclosure	Visual observations of behavioral responses within experimental context in laboratory conditions	Yes	Exposure RLs 180-200 dB SPL; severity scores: 0 & 8
Rendell & Gordon (1999)	Not included	Long-finned pilot whales	Active military sonar	Insufficient data for this analysis	Passive acoustic measurements of whistle rates	No	N/A
Chilvers & Corkeron (2001)	Not included	Bottlenose dolphins	Vessel noise and presence	Insufficient data for this analysis	Visual observations of individual foraging behavior	No	N/A
Bordino et al. (2002)	Not included	Franciscana dolphins	ADDs	Insufficient data for this analysis	Insufficient data for this analysis	No	N/A
Williams et al. (2002)	Not included	Killer whales	Vessel noise and presence	Acoustic measurements of source levels but no estimates of RL	Visual observations of movement and diving behavior	No	N/A
Cox et al. (2003)	Not included	Bottlenose dolphins	ADDs	Insufficient data for this analysis	Visual observations of movement and diving behavior	No	N/A
Hastie et al. (2003)	Not included	Bottlenose dolphins	Vessel noise and presence	Insufficient data for this analysis	Visual observations of movement and diving behavior	No	N/A
Lusseau (2003)	Not included	Bottlenose dolphins	Vessel noise and presence	Insufficient data for this analysis	Visual observations of movement behavior	No	N/A
Foote et al. (2004)	Not included	Killer whales	General increase in vessels	Insufficient data for this analysis	Insufficient data on individual exposures/ responses for this analysis	No	N/A

Table 17. Number (in **bold**) of mid-frequency cetaceans (individuals and/or groups) reported as having behavioral responses to nonpulses; responses were categorized into 10-dB RL bins, ranked by severity of the behavioral response (see Table 4 for severity scaling), and combined with other observations having the same RL/severity score. A summary of the individual studies included in this table is given in the "Mid-Frequency Cetaceans/Nonpulses (Cell 6)" section of this chapter. Parenthetical subscripts indicate the reference reporting the observations as listed in Table 16.

	Received RMS sound pressure level (dB re: 1 μPa)											
Response score	80 to < 90	90 to < 100	100 to < 110	110 to < 120	120 to < 130	130 to < 140	140 to < 150	150 to < 160	160 to < 170	170 to < 180	180 to < 190	190 to < 200
9												
8		**1.0** (3)	**7.0** (3)		**5.0** (2)		**1.0** (7)				**5.0** (13)	**1.5** (13)
7												
6				**3.0** (2, 10)	**1.0** (2)				**1.0** (9)	**6.0** (12)		
5					**1.0** (11)							
4				**1.0** (4)	**2.0** (4)							
3	**5.0** (1)		**4.0** (3, 5)	**134** (4, 6)	**1.0** (4)							
2				**15.0** (2, 3, 8)								
1			**1.0** (4)	**1.0** (2, 3)	**1.0** (2, 4)							
0			**8.0** (3, 4)	**2.0** (2, 4)	**1.0** (2, 4)		**1.0** (2)				**3.0** (13)	**1.5** (13)

Courtesy: A. Friedlander

Table 18. Summary of behavioral responses of high-frequency cetaceans exposed to nonpulses (Cell 9) by type of sound source, available acoustic metrics, description of behavioral response (by individual and/or group), and a summary of corresponding severity score(s); specific severity scores for each study are given in Table 19 and more details are given in Appendix C. Exposure RLs are given in dB SPL, which are RMS sound pressure levels (dB re: 1 µPa).

Study	Reference number (for Table 19)	Subject species	Sound source	Type of acoustic measurements	Type of individual and/or group behavioral responses	Study included in severity scale	Summary of severity scale analysis (see Table 19)
Culik et al. (2001)	1	Harbor porpoises (wild)	PICE pinger	RL estimates based on source and environmental characteristics	Visual observations of individual and group movements and behavioral patterns before and following deployment	Yes	Exposure RLs 80-120 dB SPL; response severity scores: 0 & 6
Olesiuk et al. (2002)	2	Harbor porpoises (wild)	Airmar® AHDs	RL estimates based on source and environmental characteristics	Visual observations of individual and group movements and behavioral patterns before and following deployment	Yes	Exposure RLs 140-160 dB SPL; response severity score: 6
Johnston (2002)	3	Harbor porpoises (wild)	Airmar® AHDs	RL estimates based on source and environmental characteristics	Visual observations of individual and group movements and behavioral patterns before and following deployment	Yes	Exposure RLs 120-130 dB SPL; response severity scores: 0 & 6
Kastelein et al. (1997)	4	Harbor porpoises (captive)	Various non-pulse sounds (laboratory)	Calibrated RL measurements made *in situ* within test enclosure	Visual observations of movement, respiration, and behavior in laboratory conditions	Yes	Exposure RLs 80-120 dB SPL; response severity scores: 0, 4 & 6
Kastelein et al. (2000)	5	Harbor porpoises (captive)	Various non-pulse sounds (laboratory)	Calibrated RL measurements made *in situ* within test enclosure	Visual observations of movement, respiration, and behavior in laboratory conditions	Yes	Exposure RLs 90-120 dB SPL; response severity scores: 0 & 6
Kastelein et al. (2005)	6	Harbor porpoises (captive)	Various nonpulse sounds (laboratory)	Calibrated RL measurements made *in situ* within test enclosure	Visual observations of movement, respiration, and behavior in laboratory conditions	Yes	Exposure RLs 90-120 dB SPL; response severity scores: 0 & 6
Kastelein et al. (2006a)	7	Harbor porpoises (captive)	Various non-pulse sounds (laboratory)	Calibrated RL measurements made *in situ* within test enclosure	Visual observations of movement, respiration, and behavior in laboratory conditions	Yes	Exposure RLs 100-120 dB SPL; response severity scores: 0 & 6

Table 18 (continued)

Study	Reference number (for Table 19)	Subject species	Sound source	Type of acoustic measurements	Type of individual and/or group behavioral responses	Study included in severity scale	Summary of severity scale analysis (see Table 19)
Kraus et al. (1997)	Not included	Harbor porpoises (wild)	Dukane® pingers	Insufficient data for this analysis	Measurements of by-catch rates in commercial fisheries	No	N/A
Taylor et al. (1997)	Not included	Harbor porpoises (wild)	General nonpulse sounds	Review analysis	Review analysis	No	N/A
Johnston & Woodley (1998)	Not included	Harbor porpoises (wild)	Various AHDs	Insufficient data for this analysis	Visual observations of "exclusion" zones	No	N/A
Cox et al. (2001)	Not included	Harbor porpoises (wild)	Various ADDs	Insufficient data for this analysis	Visual observations of "exclusion" zones	No	N/A
Kastelein et al. (2001)	Not included (same subjects as 2000 study)	Harbor porpoises (captive)	Various nonpulse sounds (laboratory)	Calibrated RL measurements made *in situ* near areas of exposure	Aerial observations of individuals; movement and respiration patterns during and without airguns	No	N/A
Barlow & Cameron (2003)	Not included	Harbor porpoises (wild)	Various ADDs	Insufficient data for this analysis	Measurements of by-catch rates in commercial fisheries	No	N/A
Koschinski et al. (2003)	Not included	Harbor porpoises (wild)	Simulated wind turbine noise	Calibrated source-level measurements made but insufficient data on RL	Visual monitoring of general distribution patterns	No	N/A

Table 19. Number (in **bold**) of high-frequency cetaceans (individuals and/or groups) reported as having behavioral responses to nonpulses; responses were categorized into 10-dB RL bins, ranked by severity of the behavioral response (see Table 4 for severity scaling), and combined with other observations having the same RL/severity score. A summary of the individual studies included in this table is given in the "High-Frequency Cetaceans/Nonpulses (Cell 9)" section of this chapter. Parenthetical subscripts indicate the reference reporting the observations as listed in Table 18.

	Received RMS sound pressure level (dB re: 1 μPa)											
Response score	80 to < 90	90 to < 100	100 to < 110	110 to < 120	120 to < 130	130 to < 140	140 to < 150	150 to < 160	160 to < 170	170 to < 180	180 to < 190	190 to < 200
9												
8												
7												
6	**0.3** (4)	**0.3** (4)	**0.9** (1, 2, 4, 5, 6, 7)	**3.3** (1, 2, 4, 5, 6, 7)	**1.0** (3, 7)		**52.1** (2)	**9.3** (2)	**4.6** (2)			
5												
4			**0.1** (4)	**0.1** (4)								
3												
2												
1												
0	**12.8** (1, 5)	**23.1** (1, 2, 5, 6)	**0.4** (4, 7)	**0.1** (7)	**0.3** (3)							

Courtesy: A. Friedlander

Table 20. Summary of behavioral responses by different species of pinnipeds in water exposed to nonpulses (Cell 12) by type of sound source, available acoustic metrics, description of behavioral response (by individual and/or group), and a summary of corresponding severity score(s); specific severity scores for each study are given in Table 21 and more details are given in Appendix C. Exposure RLs are given in dB SPL, which are RMS sound pressure levels (dB re: 1 µPa).

Study	Reference number (for Table 21)	Subject species	Sound source	Type of acoustic measurements	Type of individual and/or group behavioral responses	Study included in severity scale	Summary of severity scale analysis (see Table 21)
Jacobs & Terhune (2002)	1	Harbor seals	Airmar® dB plus II AHD	RLs measured *in situ* in areas where individuals observed	Visual observations of individuals and groups of seals; movement and behavioral patterns during and without AHDs	Yes	Exposure RLs 120-130 dB SPL; response severity score: 0
Costa et al. (2003)	2	Elephant seals	ATOC (see Appendix B)	RLs measured using calibrated archival tags *in situ* on individuals during exposure	Archival tags placed on animals resulted in detailed quantitative measures of individual diving behavior, responses, and exposure RLs in well-characterized contexts	Yes	Exposure RLs 110-140 dB SPL; response severity scores: 0, 3 & 4
Kastelein et al. (2006b)	3	Harbor seals	Various nonpulse sounds used in underwater data communications	Calibrated RL measurements made *in situ* within experimental enclosure	Individual subject positions and the mean number of surfacing behaviors during control and exposure intervals	Yes	Exposure RLs 80-110 dB SPL; response severity scores: 0 & 6
Frost & Lowry (1988)	Not included	Ringed seals	Underwater drilling sounds	Insufficient data for this analysis	Insufficient data for this analysis	No	N/A
Richardson et al. (1990b, 1991)	Not included	Ringed and bearded seals	Underwater drilling sounds	Insufficient data for this analysis	Insufficient data for this analysis	No	N/A
Norberg & Bain (1994)	Not included	California sea lions	Cascade Applied Sciences® AHDs	Calibrated acoustic measurements taken around arrays of the devices	Insufficient data on individual responses for this analysis	No	N/A
Norberg (2000)	Not included	California sea lions	Airmar® dB plus II AHD	Insufficient data for this analysis	Some behavioral measurements but insufficient data on individual responses as a function of RL	No	N/A
Yurk (2000)	Not included	Harbor seals	AHD	Insufficient data for this analysis	Insufficient data for this analysis	No	N/A
Koschinski et al. (2003)	Not included	Harbor seals	Simulated wind turbine noise	RLs measured *in situ* in areas where individuals observed	Insufficient data on individual responses for this analysis	No	N/A
Moulton et al. (2003)	Not included	Ringed seals	Construction noise	Insufficient data for this analysis	Insufficient data on individual responses for this analysis	No	N/A

Table 21. Number (in **bold**) of pinnipeds in water (individuals and/or groups) reported as having behavioral responses to nonpulses; responses were categorized into 10-dB RL bins, ranked by severity of the behavioral response (see Table 4 for severity scaling), and combined with other observations having the same RL/severity score. A summary of the individual studies included in this table is given in the "Pinnipeds in Water/Nonpulses (Cell 12)" section of this chapter. Parenthetical subscripts indicate the reference reporting the observations as listed in Table 20.

	Received RMS sound pressure level (dB re: 1 μPa)											
Response score	80 to < 90	90 to < 100	100 to < 110	110 to < 120	120 to < 130	130 to < 140	140 to < 150	150 to < 160	160 to < 170	170 to < 180	180 to < 190	190 to < 200
9												
8												
7												
6			**1.0**$_{(3)}$									
5												
4					**1.0**$_{(2)}$	**5.0**$_{(2)}$						
3					**1.0**$_{(2)}$	**2.0**$_{(2)}$						
2												
1												
0	**1.0**$_{(3)}$	**1.0**$_{(3)}$		**1.0**$_{(2)}$	**5.0**$_{(1, 2)}$							

Courtesy: A. Friedlander

Table 22. Summary of behavioral responses by different species of pinnipeds in air exposed to nonpulses (Cell 15) by type of sound source, available acoustic metrics, description of behavioral response (by individual and/or group), and a summary of corresponding severity score(s); specific severity scores for each study are given in Table 23 and more details are given in Appendix C. Exposure RLs are given in dB SPL, which are RMS sound pressure levels (dB re: 20 µPa).

Study	Reference number (for Table 23)	Subject species	Sound source	Type of acoustic measurements	Type of individual and/or group behavioral responses	Study included in severity scale	Summary of severity scale analysis (see Table 23)
Thorson et al. (1999)	1	Harbor seals, northern elephant seals, California sea lions, and northern fur seals	Athena 2 IKONOS-1 missile launch	RLs measured *in situ* in and around breeding rookeries	Visual observations of movement and behavior of individuals in breeding rookeries before, during, and after rocket launches	Yes	Exposure RLs 110-120 dB SPL; response severity score: 6
Thorson et al. (2000b)	2	Harbor seals, northern elephant seals, and California sea lions	Titan IV B-28 missile launch	RLs measured *in situ* in and around breeding rookeries	Visual observations of movement and behavior of individuals in breeding rookeries before, during, and after rocket launches	Yes	Exposure RLs 60-70 and 110-120 dB SPL; response severity scores: 0 & 6
Berg et al. (2002)	3	Harbor seals	Titan IV B-34 missile launch	RLs measured *in situ* in and around breeding rookeries	Visual observations of movement and behavior of individuals in breeding rookeries before, during, and after rocket launches	Yes	Exposure RLs 110-120 dB SPL; response severity score: 6
Allen et al. (1984)	Not included	Harbor seals	Aerial vessel noise and presence	Insufficient data for this analysis	Insufficient data for this analysis	No	N/A
Gentry et al. (1990)	Not included	Northern fur seals	Underground explosions and quarrying operations	Insufficient data for this analysis	Insufficient data for this analysis	No	N/A
Suryan & Harvey (1998)	Not included	Harbor seals	Aerial vessel noise and presence	Insufficient data for this analysis	Insufficient data for this analysis	No	N/A
Thorson et al. (1998)	Not included	Harbor seals	Titan IV A-18 missile launch	RLs measured *in situ* in and around breeding rookeries	Insufficient data for this analysis	No	N/A
Born et al. (1999)	Not included	Ringed seals	Aircraft noise and presence	Insufficient data for this analysis	Insufficient data for this analysis	No	N/A
Thorson et al. (2000a)	Not included	Harbor seals	Titan II G-13 missile launch	RLs measured *in situ* in and around breeding rookeries	Insufficient data for this analysis	No	N/A
Berg et al. (2001)	Not included	California sea lions and northern elephant seals	Delta II EO-1 missile launch	RLs measured *in situ* in and around breeding rookeries	Insufficient data for this analysis	No	N/A
Moulton et al. (2002)	Not included	Ringed seals	Industrial equipment noise & presence	Insufficient data for this analysis	Insufficient data for this analysis	No	N/A
Holst et al. (2005a, 2005b)	Not included	Harbor seals, California sea lions, and northern elephant seals	Small- and mid-sized missile launches	RLs measured near observed pinnipeds, including peak, RMS, SEL, and duration	Visual observations of animal presence and distribution before launches and behavior during and following launches	No	N/A

Table 23. Number (in **bold**) of pinnipeds in air (individuals and/or groups) reported as having behavioral responses to nonpulses; responses were categorized into 10-dB RL bins, ranked by severity of the behavioral response (see Table 4 for severity scaling), and combined with other observations having the same RL/severity score. A summary of the individual studies included in this table is given in the "Pinnipeds in Air/Nonpulses (Cell 15)" section in this chapter. Parenthetical subscripts indicate the reference reporting the observations as listed in Table 22.

	Received RMS sound pressure level (dB re: 20 µPa)						
Response score	50 to < 60	60 to < 70	70 to < 80	80 to < 90	90 to < 100	100 to < 110	110 to < 120
9							
8							
7							
6							**1.0** $_{(1, 2, 3)}$
5							
4							
3							
2							
1							
0		**1.0** $_{(2)}$					

Courtesy: Peter M. Scheifele

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5. Research Recommendations

The marine mammal noise exposure criteria proposed here represent a synthesis and precautionary application of current scientific information. Clearly, the reliance on extrapolation procedures, extreme data gaps and limitations in many areas, and precautionary assumptions throughout point to the need for targeted research to fill specific gaps in support of subsequent criteria. We consider the current noise exposure criteria to be merely an initial step in an iterative process to understand and better predict the effects of noise on marine mammal hearing and behavior.

Research recommendations are given below in several broad categories relevant to improving marine mammal noise exposure criteria. No prioritization is implied in the ordering of these areas or research topics within them, however, and this is by no means an exhaustive list. We present, in abbreviated form, what we regard as critical, targeted research needs to improve future iterations of these exposure criteria. Some of the most important research recommendations are summarized in Table 24; each is discussed in more detail in the relevant section below. Many of these research recommendations are similar to recommendations made previously (NRC, 1994, 2000, 2003, 2005; Richardson et al., 1995). Although there has been progress in the last decade, much important work remains to be done.

Measurements of Anthropogenic Sound Sources and Ambient Noise

Comprehensive and systematic measurements are needed of all relevant anthropogenic sound sources that have a reasonable likelihood of adversely affecting marine mammal hearing or behavior. Empirical measures of sound fields enable more accurate estimation of RLs using propagation models and validate the selection of different propagation models as appropriate. Such studies must report the full range of relevant standard acoustic measurements and should include detailed information about equipment calibration and/or propagation modeling methods used (e.g., Goold & Fish, 1998; Wales & Heitmeyer, 2002; Blackwell et al., 2004a). Measurements are also needed to describe conditions where sounds classified as pulses at the source transition to nonpulse exposures. To measure *in situ* exposures from specific sound sources, archival acoustic tags should be deployed on free-ranging marine mammals and/or platforms near the animals in controlled exposure conditions.

If future noise exposure criteria are to consider the important matters of auditory masking, cumulative exposure effects on individuals, and ecosystem effects (discussed below), additional data are needed concerning ambient ocean noise on various spatial and temporal scales. These data should be used to determine how ambient noise "budgets" vary as a function of natural and human activities. These data will need to be integrated with expanded information on marine mammal abundance and distribution. The NRC (2003) recommended that a systematic effort be made to obtain passive acoustic data, including average (steady-state) ambient noise from 1 Hz to 200 kHz, and including transient human sources not identified in classical ambient noise measurements. We concur and call for wide-ranging acoustic measurements designed to test explicit hypotheses about spatial and temporal variability in marine ambient noise.

Marine Mammal Auditory Processes

"Absolute" Hearing Data

Future iterations of these criteria will be significantly improved by increased knowledge of hearing sensitivity derived from behavioral and electrophysiological measurements and anatomical models. The most pressing needs are for data on deep-diving cetaceans such as beaked whales and on low-frequency specialists (mysticetes). Better information on inter-species differences is also needed to validate the functional hearing groups used here or alternatively to identify other relevant subdivisions (e.g., phocid vs otariid pinnipeds or potential partitioning of mid-frequency cetaceans). The number of individuals tested should be increased in all species, with the possible exception of the bottlenose dolphin, in order to better understand individual differences within species. Hearing sensitivity across the full functional hearing range should be measured, where possible, rather than just those frequencies contained within the communication signals of species being investigated.

Improvements are needed in both electrophysiological and behavioral testing methods to increase the number of individuals of each species that can be tested, and to distinguish absolute

Table 24. Research recommendations in various subject areas needed to enhance future marine mammal noise exposure criteria (as discussed in Chapter 5)

Research topic	General description	Critical information needs
Acoustic measurements of relevant sound sources	Detailed measurements needed of source levels, frequency content, and radiated sound fields around intense and/or chronic noise sources.	Comprehensive, calibrated measurements of the properties of human-generated sound sources, including frequency-dependent propagation and received characteristics in different environments.
Ambient noise measurements	Systematic measurements of underwater ambient noise are needed to quantify how human activities are affecting the acoustic environment.	Comprehensive, calibrated measurements of ambient noise, including spectral, temporal, and directional aspects, in different oceanic environments; ambient noise "budgets" indicating relative contribution of natural and anthropogenic sources and trends over time.
"Absolute" hearing measurements	Audiometric data are needed to determine functional bandwidth, species and individual differences, dynamic hearing ranges, and detection thresholds for realistic biological stimuli.	Carefully controlled behavioral and electrophysiological measurements of hearing sensitivity vs frequency for more individuals and species, particularly for high-priority species, such as beaked whales and mysticetes. Also, detection thresholds for complex biological signals.
Auditory scene analysis	Measurements to determine the sophisticated perceptual and processing capabilities of marine mammals that enable them to detect and localize sources in complex, 3-D environments.	Measurements of stream segregation, spatial perception, multidimensional source localization, frequency discrimination, temporal resolution, and feedback mechanisms between sound production and hearing systems.
Marine mammal behavioral responses to sound exposure	Measurements of behavioral reactions to various sound types are needed, including all relevant acoustic, contextual, and response variables.	Carefully constructed observational and exposure experiments that consider not only RL but also source range, motion, signal-to-noise ratio, and detailed information on receivers, including baseline behavior, prior experience with the sound, and responses during exposure.
Effects of sound exposure on marine mammal hearing: masking, TTS, and PTS	Continued effort is needed on the simultaneous and residual physiological effects of noise exposure on marine mammal hearing.	Masked hearing thresholds for simple stimuli in more species and individuals, as well as complex biological signals and realistic maskers; allowance for directional effects; comparative data on TTS-onset and growth in a greater number of species and individuals for nonpulse and pulsed anthropogenic sources; recovery functions after exposures and between repeated exposures.
Effects of sound exposure on marine mammal non-auditory systems	Physiological measurements are needed for both acute and chronic sound exposure conditions to investigate effects on non-auditory systems.	Various baseline and exposure-condition measurements, including nitrogen saturation levels; bubble nuclei; the formation of hemorrhages, emboli, and/or lesions; stress hormones; and cardiovascular responses to acute and chronic noise exposure.
Particularly sensitive species: beaked whales	Baseline and exposure data on these poorly understood taxa to assess their apparent sensitivity to certain anthropogenic sound sources.	Various studies, including measurements and modeling related to (1) hearing sensitivity, (2) diving and vocalization parameters, (3) tissue properties, (4) gas/fat emboli formation and significance, (5) advanced detection capabilities for localizing and tracking them, and (6) behavioral reactions to various anthropogenic and natural sound sources.

from masked thresholds. Auditory evoked potential (AEP) techniques should continue to be improved and standardized for pinnipeds and small cetaceans. Researchers should continue to develop procedures applicable to stranded individuals of species generally not represented in captive settings, particularly for species that may be especially sensitive to certain types of acoustic exposure. The massive body size of mysticetes may require that AEP studies begin using smaller species (e.g., minke whale) that may be stranded, trapped in tidal fishing enclosures (weirs), or temporarily available in a holding facility. Behavioral audiometric methods, which investigate the effect of the overall perceptual and cognitive system on detection, should also continue to be employed and improved, particularly those that increase the speed with which results are obtained without sacrificing precision of measurements.

Additionally, behavioral methods should be developed to measure hearing characteristics that require a subjective judgment of perception such as evaluation of equal loudness between two acoustic stimuli. Equal-loudness hearing contours for marine mammals are needed to refine the broad frequency-weighting networks derived here.

A final consideration is that behavioral audiometric research should eventually move beyond the use of relatively simple artificial stimuli (e.g., pure tones, noise bands, broadband clicks, tone pips). Such stimuli can be precisely controlled and can be used to clearly indicate which acoustic feature triggers the response in the whole animal or its auditory system. Animals in nature, however, rarely encounter such sounds. While some biological signals consist of combinations of tonal elements, most are exceedingly complex. Marine mammal detection thresholds for complex, biologically relevant stimuli may be poorly predicted by experiments using simple artificial stimuli. Humans, for example, are particularly adept at identifying speech-like sounds in noise (Yost, 2000). Animals are expected to be similarly sensitive to important natural sounds. To base future noise criteria on more relevant audiometric data, research is needed on detection thresholds for biologically meaningful sounds, such as vocalizations of conspecifics, prey, and predators, and sounds needed for active or passive acoustic navigation. Such measurements will further be useful in investigating the potential active space (detection range in three dimensions) for acoustic communication (e.g., Brenowitz, 1982; Janik, 2000; Au et al., 2004) and the effects of anthropogenic sound on the active space. Field studies using biologically relevant sounds would be more relevant to real-world communication and masking than studies involving simple, artificial test stimuli.

Auditory Scene Analysis

While baseline hearing information is clearly needed, urgently in some cases, more advanced, comprehensive, and innovative measurements are also needed that provide insight into the ways in which animals use their auditory sense to derive detailed information about their surrounding environment. For future iterations of noise exposure criteria to consider multiple stimuli and cumulative effects, additional data will be needed on sound localization in three-dimensional auditory space, frequency discrimination, temporal resolution, and, specifically, detection of biological signals in complex sound fields.

Several studies of terrestrial animals (MacDougall-Shackleton et al., 1998; Moss & Surlykke, 2001) have investigated how subjects process multiple acoustic stimuli that are simultaneously present but differ in acoustic signature either temporally or spatially. The acoustic scene concept, owing largely to the work of Bregman (1990), has the potential to play a major role in the development and progression of acoustic exposure criteria. Bregman draws powerful analogies between modalities of perception, including the fundamental ways in which higher processing systems associate common elements of complex stimuli in highly cluttered perceptual environments.

One analogy that Bregman (1990) makes with regard to the innate power of visual scene analysis is the ability of the visual processing portion of the human brain to estimate object size without regard to distance. The implication is that the reverse is true as well—if the size of something is known, its distance can be inferred from visual appearance. Extending this ability to animals that rely on underwater hearing to determine distance, similar perceptual processes may occur. If so, mammals may determine range by using various effects of the propagation medium on sound transmission (e.g., presence of structured multi-path signal spreading, frequency dependent multi-path losses, and absorption effects in particular; Ellison & Weixel, 1994). Further, both loudness modulation and source movement relative to the receiver provide significant clues as to the distance and general nature of the sound source. If one considers sound to play a role in the life of marine wildlife similar to that of sight in terrestrial animals, then context clues such as tempo, encroachment, and proximity must take on a powerful role in determining an animal's response to any given sound. These hypotheses need to be studied in marine mammals.

Behavioral Responses of Marine Mammals to Sound

There is an urgent need for better and more extensive data on behavioral responses to sound, including measurement of the specific acoustic features of exposures and consideration of previous experience with the sound and all relevant contextual variables. The current behavioral exposure criteria are quite limited in several ways. Insufficient data exist to support criteria other than those based on SPL alone, and this metric fails to account for the duration of exposure beyond the separation of pulse from nonpulse sounds. Also, there is much variability in responses among species of the same functional hearing group and also within species.

Because of the poorly understood modifying influences of numerous variables, behavioral responses usually cannot be predicted *a priori* with much confidence given present information. In addition, the biological significance of any observed behavioral response is even more difficult to assess (NRC, 2005).

Research is needed to quantify behavioral reactions of a greater number of free-ranging marine mammal species to specifically controlled or well-characterized exposures from different human sound sources. The most direct way to obtain these kinds of extremely detailed data would be to attach acoustic dosimeter tags to individuals and directly measure noise exposure, behavioral response, and physiological changes, if any. It is essential that future research investigates responses in contexts as similar as possible to those of interest. Responses of both naïve and previously exposed individuals should be studied and distinguished to the greatest extent possible.

Further, such experiments must ensure that all relevant acoustic measurements of sound exposure be reported more systematically than in many previous studies. Specifically, behavioral responses need to be directly correlated with the physical parameters (e.g., SPL, SEL) of the stimuli most likely to evoke the responses. Such research clearly requires greater knowledge of exposure parameters (including SPL over some duration) than currently exists for most studies.

The relationship between exposure SPL and/or SEL and behavioral reaction should be determined for representative species within each functional hearing group. Whether the relationship follows a dose-response-like function for various sound types, and under what conditions, is a significant and pressing open question.

We need more data on the magnitude and time course of behavioral responses to known noise exposures to test the validity of concepts outlined here, and to make progress toward identifying specific behavioral criteria. Duty cycle (the proportion of time when the noise is present) is also likely to be important. Magnitude and duration of response are the most readily quantified parameters that may be useful in determining whether a behavioral response is likely to have a biologically meaningful outcome. Noise exposure criteria should attempt to distinguish between minor, temporary behavioral changes and those with greater significance. This is necessary in order to focus on biologically significant behavioral responses (see NRC, 2005) and the exposure conditions that elicit them.

Considering the many contextual cues that free-ranging animals use to perceive and characterize sound sources and to determine a response, it is not surprising that our analysis revealed a high degree of variability in behavioral responses as a function of RL. Consequently, the logic of relying solely on exposure RL as the metric for behavioral responses is substantially diminished. A host of variables additional to RL may be important to marine mammals in assessing a sound and determining how to react. This argues for careful design and execution of controlled exposure experiments to replicate the signal of interest in as many dimensions as possible. Serious consideration should be given to developing a broad multi-variable approach to behavioral research that takes into account not only source type and exposure level but also distance, motion, and relative signal-to-noise ratio. Some studies are already developing data of the scale and quality needed for such an approach. This includes studies providing broad, long-term measurements of ambient sounds in areas cohabited by anthropogenic sources and marine wildlife. Where these studies include remotely deployed passive acoustic sensors and tagged animals, they approach what may become the new standard. As additional information becomes available, future noise exposure criteria may assess behavioral reactions not only according to RL measured with multiple acoustic parameters, range (near and far), relative motion (towards, parallel, etc.), and rate of change, but also in relation to the animal's activity or perceptual situation (e.g., neutral; threatened, as by a predator; or positive, related to food, mating, etc.).

The role of habituation and sensitization in behavioral reactions to noise exposure is a critical subject for future research. These processes can only be studied under controlled or well-defined conditions (as in Deecke et al., 2002). A key question is how habituation and sensitization develop with repeated exposure in specific ecologically relevant circumstances. For example, the pattern of habituation to a neutral stimulus is likely to follow quite a different pattern from selective habituation to a harmless stimulus that is initially perceived as a threat (Deecke et al., 2002). Furthermore, it would be desirable to know if there are common acoustic features in sounds to which marine mammals become sensitized. For example, to which acoustic features of a threat, such as a vessel used to hunt animals, does an animal become sensitized?

Analyses of the behavior of various animal species in the presence of predators suggest that they have evolved anti-predator responses that mirror their responses to human disturbance. According to predation risk theory, various ecological considerations beyond simply disturbance magnitude are very likely involved in determining and predicting behavioral response (Frid & Dill, 2002).

The biological relevance of behavioral changes can only be determined in natural populations in which vital life history parameters (e.g., reproduction, growth, and survival rates) can be measured before and after noise exposure and in conditions where other potential stressors have been controlled (NRC, 2005). One important question is whether these life history parameters are the same in populations that have apparently habituated to exposure and remain in relatively noisy environments as they are in populations living in quieter conditions. Because of the apparently major influence of experience and the strong context-specificity of behavioral responses to noise, field measurements must be made for long periods following repeated or continual exposure. Longitudinal studies should be conducted to assess the time course of exposure to various existing sound sources known or suspected to cause relatively long-term (seasonal) habitat abandonment. Where possible, parallel studies should be done in neighboring areas with different levels of noise exposure. Such studies should allow for other non-acoustic factors likely to affect distribution such as predators, prey, and other important environmental covariates. These studies will often need to extend over long periods (many years) in order to be effective, and they should be planned and funded recognizing that. Ideally, such a study should start collecting data well in advance of the introduction of anthropogenic noise, and continue throughout the period of anticipated impact and for long enough thereafter to observe return to baseline.

Effects of Noise Exposure on Marine Mammal Hearing and Other Systems

Auditory Masking

Auditory masking is likely the most widespread effect of anthropogenic noise on populations of marine mammals. The principles of masking are reasonably well-known from laboratory studies in mammals, including marine mammals. To enable masking to be included in subsequent noise exposure criteria, however, data are needed on masking and its effects in real-world conditions for all functional hearing groups. Data are needed on the masking effects of natural and anthropogenic noise sources; on detection of simple, artificial stimuli; and, increasingly, on more complex, biologically meaningful signals. Directionality in the masking sound and/or the signal of interest is very likely to affect the severity of masking and needs to be considered. Baseline measurements are needed on functional communication ranges for different acoustic signals and on the reduction of those ranges caused by either natural or anthropogenic maskers. Also needed are additional field measurements of the behavioral adjustments that marine mammals make to offset masking effects (e.g., Lesage et al., 1999; Serrano & Terhune, 2002; Foote et al., 2004; Scheifele et al., 2005).

Temporary Threshold Shift (TTS)

TTS studies in marine mammals remain limited to a very few species and individuals, limiting the certainty with which they may be extrapolated within and among groups. A number of specific TTS studies are needed to improve future criteria. For instance, it is critical to future iterations of these noise exposure criteria that research on TTS-onset, TTS growth with noise exposure, and recovery rates expands to larger numbers of individuals and species, and to species in the low- and high-frequency cetacean groups. Presently, extrapolation procedures must be used because TTS data are unavailable for certain functional hearing groups. Additionally, certain highly precautionary procedures are used here in the estimation of PTS-onset because the growth rate of TTS with increasing exposure level is generally poorly understood, even for the few marine mammal species in which TTS has been studied. The relationship between auditory sensitivity and susceptibility to TTS/PTS should be determined by group.

To the extent possible, electrophysiological techniques should be used to obtain these TTS data to increase sample size and knowledge of recovery functions.

More data for pinnipeds also are needed, particularly for pulse exposures where extrapolations of cetacean data currently must be used. Particular emphasis should be placed on determining whether harbor seals have increased sensitivity to noise exposure relative to other pinniped species, as current information suggests, and if so, whether species closely related to the harbor seal also are more sensitive than are other pinnipeds.

To minimize the need for such extrapolation and reduce the assumptions required to predict PTS-onset, empirical data are needed on TTS growth rates up to greater shift magnitudes (10 to 30 dB). These data are needed for both pulse and nonpulse sound types, at a variety of exposure frequencies, in both single and multiple exposures. These results should further elucidate whether, and in what conditions, the "equal energy hypothesis" may be appropriate for comparing the effects of variable noise exposures in marine mammals. For pulse exposures, particular attention should be paid to whether TTS growth is directly related to overall noise energy, and whether the kurtosis of exposure is also a factor (see Erdreich, 1986; Thiery & Meyer-Bisch, 1988; Dunn et al., 1991; Hamernik et al., 1993, 2003).

A further topic for future research is determining whether using 40 dB of TTS as a proxy for PTS-onset is a precautionary approach, and whether TTSs on the order of 25 to 35 dB are fully recoverable in marine mammals as expected from terrestrial mammal data. To avoid any possibility of injury, such studies should continue to take a precautionary approach, using gradual increases in exposure level and duration.

A related question is how TTS recovers following noise cessation in variable conditions. Data on recovery functions and TTS magnitude are needed for representative species from each functional hearing group. Electrophysiological techniques may be particularly useful in this regard. These data may be useful in comparing basic auditory system responses to noise exposure and determining how summation procedures for multiple exposures should be modified to more precisely consider exposure intermittence. Levels of relatively long duration noise exposure causing asymptotic TTS, in which TTS values do not continue to increase in magnitude with exposure but may have longer-lasting effects, should be determined. Recovery functions from asymptotic TTS of various levels should be compared with recovery functions from non-asymptotic TTS.

Finally, the existence of a stapedial reflex in marine mammals and its possible role in mitigating TTS and other effects of intense noise exposure are areas of needed research. For certain noise exposures, particularly those with relatively low frequencies and long duration, the middle ear muscles (tensor tympani and stapedial) of terrestrial mammals may contract and reduce the amplifying function of the ossicular chain (Yost, 2000). This muscular contraction reduces the amount of acoustic energy transmitted into the cochlea via the stapes. This stapedial reflex has been demonstrated in humans exposed to intense sound (Davis et al., 1955) as well as echolocating bats exposed to their own intense outgoing clicks (Henson, 1965). The middle ears of marine mammals have some specialized adaptations relative to terrestrial mammals (see Wartzok & Ketten, 1999). In water, if bone conduction (rather than ossicular conduction) is the predominant transmission path, it is possible that a stapedial reflex, if present, may have limited or no protective function for intense acoustic exposures. Research is also needed on the role of meatal closure in pinnipeds during noise exposure. Such closures could be an alternative or additional way of reducing auditory sensitivity. Either mechanism could also affect the interpretation of threshold if performed during audiometric measurements.

Permanent Threshold Shift (PTS)

Sound exposures causing PTS-onset, used here to define injury from acoustic exposure, have not been measured in marine mammals. Instead, exposures that would cause PTS-onset are estimated from measured TTS-onset using assumptions about the growth of TTS with noise exposure level. Direct measurements of PTS in marine mammals are highly desirable for establishing future injury criteria, but they are unlikely to be obtained due to ethical, legal, and/or practical considerations. Data from modeling and exposure of cadavers to very intense acoustic stimuli give some indication of conditions causing PTS but do not reveal the exposure conditions that produce PTS *in vivo*, nor active processes that affect basilar membrane displacement. Consequently, our research recommendations for improving PTS-onset predictions for marine mammals involve more indirect measures.

One recommended type of indirect measure is to compare age-related hearing changes in captive individuals that have been involved in TTS experiments with those that have not. This comparison may provide some insight into the complex relationship between repeated TTS and PTS, which remains poorly understood for terrestrial mammals, including humans. One main impediment, however, is that confounding variables likely exist other than controlled noise exposure. For captive individuals used in TTS studies, absolute hearing should be tested both during and following sequences of noise exposure experiments. For captive individuals not used in TTS experiments, absolute hearing should be measured at regular intervals over extended periods. The latter group may more readily display natural age-related hearing loss (*presbycusis*) than the former, as well as potential sex differences. For both groups, efforts should be made to characterize long-term ambient noise conditions experienced by test animals.

Non-Auditory Effects of Noise Exposure

Lack of specific data on acoustic exposures causing non-auditory effects in marine mammals currently prevents deriving explicit exposure criteria for such effects. Research is underway, however, that may make this possible in future versions of the criteria. Non-auditory effects of noise are potentially significant but remain generally poorly understood.

A current hypothesis regarding non-auditory effects is that acoustic exposure may produce nitrogen bubbles in blood or other tissues. Hemorrhages, gas and fat emboli, and other lesions have been reported in some marine mammals exposed to mid-frequency military sonar (Jepson et al., 2003; Fernández et al., 2004, 2005). Substantial empirical questions remain, however. First among these is whether nitrogen bubbles are in fact responsible for the hemorrhages, emboli, and other lesions reported. Conversely, are enough nitrogen bubbles produced to pose a risk of related tissue injuries, under any set of circumstances, arising from high nitrogen supersaturation levels, acoustic exposure, and/or drastic changes in behavior? Do high levels of nitrogen supersaturation or gas or fat emboli occur in diving mammals that have not been exposed to intense anthropogenic sound? Do these or related phenomena occur in species other than beaked whales? If bubble formation is acoustically mediated, does it occur as a direct result of acoustic exposure of bubble precursors (nuclei) in tissue, or indirectly through changes in diving behavior? If the pathway is direct, how does bubble formation and/or growth occur? A more thorough understanding is needed of lipid biochemistry in tissues that may be particularly sensitive to acoustically mediated bubble formation (e.g., acoustic fats). Modeling studies are needed on tissue properties and their relevance to nitrogen bubble formation at specific frequencies of interest. These studies should consider the growth of discrete bubbles from precursors in various tissues, and the interaction among coalesced aggregations of acoustically activated bubbles.

If the pathway is indirect and mediated by behavior, is rapid surfacing more risky than remaining submerged too long and exceeding physiological limits? How does the dive profile affect the limits of nitrogen supersaturation in normal diving? Do high levels of nitrogen supersaturation and gas emboli occur in marine mammals that have voluntary control over depth, diving profile, and inter-dive interval? Resolution of these questions is likely to require interplay between modeling and empirical measurements (Zimmer & Tyack, 2007).

In conjunction with the above physiological modeling and measurements, controlled exposure experiments should be conducted with deep-diving marine mammals to determine behavioral responses to sound sources, including sonar. These experiments should use realistic source and received levels. If responses are identified, this may identify situations where it would be useful to conduct observational studies of responses during uncontrolled use of anthropogenic sound sources. Research should characterize the changes in diving behavior and should determine what they mean in terms of bubble formation or growth with continued exposure.

Other possible non-auditory effects of acoustic exposure should be investigated as well. Stress hormone levels associated with noise exposure should be more fully investigated. As of now, they have been investigated following exposure of captive odontocetes to high-level sound (Thomas et al., 1990c; Romano et al., 2004). The ability of animals to recruit effective stress responses should also be studied during chronic exposures—for example, in captive animals that live permanently in noisy vs quiet environments. Effects of noise exposure on marine mammal vestibular and cardiovascular systems should also be studied.

Particularly Sensitive Species

In rare circumstances, marine mammals (primarily beaked whales) have been known to strand and ultimately die following exposure to tactical, mid-frequency active sonar (see Cox et al., 2006; Nowacek et al., 2007). Our knowledge of these kinds of extreme reactions to acute exposures remains poor. However, the available information suggests that at least some species of beaked whales are particularly sensitive to this one specific category of sound sources.

Gas bubble formation is a hypothesized pathway of this effect (e.g., Fernández et al., 2005), but it remains poorly understood and the precise mechanism underlying these strandings remains unknown (e.g., Cox et al., 2006). The controlled exposure experiments outlined above are essential to revealing the conditions and responses underlying this effect. Until such research is conducted, deriving science-based exposure criteria specifically for beaked whales or other deep-diving cetaceans exposed to active sonar will prove difficult or impossible.

One current hypothesis is that behavioral reactions influence beaked whale diving patterns in a way that induces physically debilitating or disorienting injuries (Cox et al., 2006). Both the specifics of this potential mechanism and whether it is specific to beaked whales remains unknown, however. Mammals, including some marine mammals, show strong avoidance responses when evading predators. Sounds from tactical mid-frequency sonars somewhat resemble, in frequency band and modulation, the social signals of one of the only predators of large marine mammals, the killer whale. If beaked whales inherit a broad template for acoustic detection of these predators, as waterfowl do for visual detection of aerial predators (Lorenz, 1939; Tinbergen, 1948), they might respond to sonar as if it were a predator. Learning is required for selective habituation to safe stimuli that resemble those from predators (Deecke et al., 2002). Many of the strandings that coincide with sonar exercises have occurred in sites where killer whales are rare. Possibly these stranded animals have not had enough experience with either sonar or killer whales to learn the difference. Propagation of sound in the ocean may also degrade acoustic features that help differentiate the two classes of stimuli at a distance. It is plausible that this type of reaction could occur at relatively long distances from the source if the sound is alarming based on properties other than high RL.

Whether beaked whales in certain conditions mistake tactical mid-frequency sonar signals for killer whales and consequently change their behavior in a way that injures them is an empirical question. This should be carefully investigated using controlled experiments that take into account the relevant contextual variables discussed above. Additional baseline data on beaked whale physiology, life history, and behavior are also needed to appropriately address questions regarding the apparent sensitivity of these animals to certain kinds of anthropogenic sound. Finally, in some specific conditions, such as sonar training ranges, where sophisticated listening arrays make it possible to detect marine mammals over large ranges before and during active sonar operations, active or passive detection of marine mammal behavioral patterns may become increasingly possible. While these observations have limitations, given that they may be able to detect more individuals without requiring tagging efforts, they may be an important complement to directed experiments.

Some other species of marine mammals are unusually responsive to certain anthropogenic sounds, either generally or under particular conditions, and this can result in strong and sometimes large-scale avoidance. Examples include harbor porpoises and, in some but not all situations, beluga and bowhead whales (Finley et al., 1990; Richardson et al., 1999; Olesiuk et al., 2002; Miller et al., 2005). There is a need for additional behavioral and acoustic information to better characterize these extreme responses, the situations in which they occur, and whether similar responses can occur in other related species or in response to other similar stimuli.

Necessary Progressions of Marine Mammal Noise Exposure Criteria

The currently proposed noise exposure criteria are for individual sound exposures and individual marine mammals. The research recommended above is needed to substantiate and improve future iterations of these types of criteria. Future iterations of behavioral disturbance criteria may derive dose-response functions based on an ordinal scoring paradigm similar to that provided. This may occur for subcategories of sound sources within the general categories here (e.g., seismic signals as a subset of multiple pulses, vessel noise as a subset of nonpulses). It may also occur for subgroups of species within the broad categories recognized here (e.g., phocid vs otariid pinnipeds) and for other types of marine mammals not addressed here (e.g., sirenians, sea otters, polar bears).

Future iterations of these noise exposure criteria should also perhaps distinguish several different categories of response that are expected, for both theoretical and empirical reasons, to vary with RL in different ways. For example, if an animal responds to a sound as if it were from a predator (Frid & Dill, 2002), one would expect the dose-response function to have a very different shape as compared to that if the animal responds based on interference with the animal's ability to communicate acoustically or echolocate. Predicting whether a sound might trigger an anti-predator response would require more detailed analyses of acoustic parameters of the anthropogenic sound compared to signals of predators. Further, in some non-marine taxa, different anti-predator responses may be triggered depending on levels and other characteristics of acoustic stimuli (Spangler, 1988; Hoy, 1989) and may be modulated by the cost of the response as well as the perceived risk (Frid & Dill, 2002). Behavioral ecologists hypothesize that anti-predator behavior should balance risk of predation against cost of response, including cost of foregone benefits from alternative activities (Frid & Dill, 2002). These non-acoustic parameters must be taken into account in order to understand disturbance responses. The acoustic parameters affecting anti-predator behavior may involve detection thresholds, ambient noise conditions, source distance and source movement, as well as the more direct measures of received sound. In future studies, most or all of these parameters should be measured.

Additionally, further exposure criteria are needed to fully consider the effects of anthropogenic noise on other types of marine life, including the effects of single and multiple exposures on individual invertebrates, fish, and sea turtles as well as sirenians, sea otters, and polar bears. There are fewer data to support criteria for marine biota other than cetaceans and pinnipeds, and criteria are perhaps as urgently (or more urgently) needed for some other groups. Some fish and most sea turtle species are considered threatened or endangered. The effects of anthropogenic noise on fish are also of particular importance given their central role as both predators and prey in many marine ecosystems and because of human dependence on fisheries.

Additional criteria are also needed for the cumulative effects of repetitive or long-term noise exposure on marine mammals. Ideally, spatiotemporal data on marine ambient noise and long-term exposure histories of individuals should be integrated with vital rate data for marine mammal populations to address this question. Considerably more data are needed on how noise impacts in single animals can be extended to the population level. Such measurements will likely require extensive measurements on a few representative species and conservative extrapolations within and between functional hearing groups.

Noise exposure criteria that consider ecosystem-level effects are needed as well. It is possible that the effects of noise exposure on some elements of local food webs may have a cascade effect to other elements within the web. No data are available on the ecological effects of underwater noise, even at a local scale. However, given the upward trend in human activities in many nearshore areas, such ecological effects should be anticipated.

Progress in each of these research areas will involve iterative processes that depend on the availability of relevant scientific data. Like the process of improving and expanding future noise exposure criteria, our ability to understand and predict the effects of anthropogenic noise exposure on marine ecosystems will continue to evolve over a period of many decades.

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Appendix A. Acoustic Measures and Terminology

This appendix provides a more detailed description of many key acoustic measurements and terms used throughout the noise exposure criteria. It is not intended as an exhaustive or instructive text on these exceedingly complex issues (for more detailed treatments, see Kinsler et al., 1982; ANSI, 1986, 1994; Richardson et al., 1995; Harris, 1998; NRC, 2003). Rather, it is intended to provide fairly straightforward definitions and equations related to the marine mammal noise exposure criteria.

Pulses and Nonpulse Sounds

The distinction between these two general sound types is important because they have differing potential to cause physical effects, particularly with regard to hearing (e.g., Ward, 1997).

Pulses, as used in the context of this paper, are defined as brief, broadband, atonal, transients (ANSI, 1986; Harris, 1998, Chapter 12). Examples of pulses (at least at the source) are explosions, gunshots, sonic booms, seismic airgun pulses, and pile driving strikes. These sounds are all characterized by a relatively rapid rise from ambient pressure to a maximal pressure value followed by a decay period that may include a period of diminishing, oscillating maximal and minimal pressures. The rapid rise-time characteristic of these sounds ensures that they are also broadband in nature, with the higher-frequency components being related to the rapidity of the rise-time. Pulses, either as isolated events or repeated in some succession, generally have an increased capacity to induce physical injury as compared with sounds that lack these features.

Nonpulse (intermittent or continuous) sounds can be tonal, broadband, or both. Some of these nonpulse sounds can be transient signals of short duration but without the essential properties of pulses (e.g., rapid rise-time). Examples of sources producing nonpulse sounds include vessels; aircraft; machinery operations, such as drilling or wind turbines; and many active sonar systems. The duration of such sounds, as received at a distance, can be greatly extended in highly reverberant environments. It is critical to note that a sound that has characteristics of a pulse at the source may, as a result of propagation effects, lose those characteristics at some (variable) distance and could be characterized as a nonpulse for certain receivers.

Pulses and nonpulses are distinguished here by an empirical approach based on several temporal weightings. Various exponential time-weighting functions applied in measuring pulse and nonpulse sounds may yield different measured received levels (RLs) (see Harris, 1998). By way of illustration, most sound level meters (SLM) provide options for applying either a slow or fast time constant (1,000 or 125 ms, respectively) for measuring nonpulses, or an impulse time constant (35 ms) appropriate for measuring pulses. If applied to a sound pulse, the slow or fast SLM settings result in lower sound pressure level (SPL) measurements than those obtained using the impulse setting. Each of these time constants was selected based on the physical properties of the human auditory system. It is clear that further empirical measures of temporal resolution in marine mammals are needed, particularly for animal taxa whose hearing extends to significantly higher or lower frequencies than in humans (see Chapter 5, "Research Recommendations"). Future noise criteria are expected to include distinctions between pulse and nonpulse sounds that may be more specifically appropriate for marine mammals than is this current simple approach. We note also the need for an explicit distinction and measurement standard, such as exists for aerial signals (ANSI, 1986).

Peak sound pressure is the maximum absolute value of the instantaneous sound pressure during a specified time interval and is denoted as P_{max} in units of Pascals (Pa). It is not an averaged pressure. Peak pressure is a useful metric for either pulse or nonpulse sounds, but it is particularly important for characterizing pulses (ANSI, 1986; Harris, 1998, Chapter 12). Because of the rapid rise-time of such sounds, it is imperative to use an adequate sampling rate, especially when measuring peak pressure levels (Harris, 1998, Chapter 18).

Peak-to-peak sound pressure is the algebraic difference between the maximum positive and maximum negative instantaneous peak pressure.

The ***mean-squared pressure*** is the average of the squared pressure over some duration. For nonpulse sounds, the averaging time is any convenient period sufficiently long enough to permit averaging the variability inherent in the type of sound. Note that some of the variability of the received sound typically arises simply from the relative movement of a free-ranging animal and a source, whether the latter is moving or stationary.

Sound pressure levels (SPLs) are given as the decibel (dB) measures of the pressure metrics defined above. The ***root-mean-square*** (RMS) SPL is given as dB re: 1 µPa for underwater sound and dB re: 20 µPa for aerial sound. Peak SPLs are given as dB re: 1 µPa (peak) in water and dB re: 20 µPa (peak) in air. Peak-to-peak SPLs are dB re: 1 µPa (peak-to-peak) in water and dB re: 20 µPa (peak-to-peak) in air. ***Source level*** (SL) is the received level measured or estimated 1 m from the source.

Duration is the length of a sound, generally in seconds. Duration is important because it affects various acoustic metrics, including mean-square and/or RMS sound pressure (Madsen, 2005). Because of background noise and reverberation, duration can be difficult to define precisely. Various definitions of duration exist in the literature such as the time between the points on the pressure-time waveform P(t) determined to be either 10 dB (0.316 times) or 20 dB (0.1 times) below the instantaneous peak pressure (Hamernik & Hsueh, 1991). Malme et al. (1983, 1984) used a similar approach. Harris (1998, Chapter 11) suggested alternative constructs, including exponential time weighting. This topic is discussed below with regard to updating measurement standards for impulse sounds. Greene (1997) described a practical definition of pulse duration based on the interval over which 90% of the sound energy arrived at the receiver. This interval could also be used as the averaging time for mean-square pressure (Madsen, 2005). This approach has been widely used in measuring exposure duration and SPL values for seismic airgun and pile driving signals (e.g., McCauley et al., 1998; Blackwell et al., 2004b). Defined as such, duration is the interval between the 5% and 95% bounds of the time-integral of the instantaneous sound-pressure squared (sound exposure [E(t)] as defined below) while accounting for background noise and low-level reverberation (assumed to be continuous). That is, the background noise is measured over a period of time before the pulse occurs and then is subtracted from the cumulative sum-of-square pressures to determine the sum-of-square pressures from the impulsive sound alone. This is done by manually identifying a period of time (t_1, t_2) preceding the event, deemed to be representative of ambient noise. The mean-square pressure (in Pa^2) of the ambient $(P_{amb})^2$ is determined with the following relationship:

$$\overline{P_{amb}^2} = \frac{1}{t_2 - t_1}\int_{t_1}^{t_2} P^2(t)dt \qquad \text{(1) eq.}$$

The ***temporal (or event) sound exposure*** E_{temp} (t) (in Pa^2-s) is then calculated as

$$E_{temp}(t) = \int_{t_2}^{t}\left(P^2(t) - \overline{P_{amb}^2}\right)dt \qquad \text{(2) eq.}$$

The 0% sound exposure point (t_a) signifies the "start" of the acoustic event and the 100% sound exposure point (t_b) signifies the "end" of the event. These two points are where the E(t) curve begins to rise and where it levels off, respectively. Their selection can be difficult due to variation in ambient noise preceding (and overlapping) the acoustic event, as well as reverberation plus ambient noise following the event. Consequently, many investigators identify these points subjectively.

The ***sound exposure E(t)*** (in Pa^2-s), where $t \le t_b$, is then calculated as

$$E(t) = \int_{t_a}^{t}\left(P^2(t) - \overline{P_{amb}^2}\right)dt \qquad \text{(3) eq.}$$

where $E_{100} = E(t_b)$ is 100% of the sound exposure. For the 5% point, E(t) is determined as $E_5 = 0.05 \bullet E_{100} = E(t_5)$, while E(t) for the 95% energy point is determined as $E_{95} = 0.95 \bullet E_{100} = E(t_{95})$. Thus, $E_{90} = E_{95} - E_5$ and duration (T_d) = $t_{95} - t_5$ (s) where the received pressure level greatly exceeds the ambient level, eq. 3 can be reduced to

$$E(t) = \int_{t_a}^{t}\left(P^2(t)\right)dt \qquad \text{(4) eq.}$$

Sound exposure level (SEL) is the decibel level of the cumulative sum-of-square pressures over the duration of a sound (e.g., dB re: 1 µPa^2-s) for sustained nonpulse sounds where the exposure is of a constant nature (i.e., source and animal positions are held roughly constant). However, this measure is also extremely useful for pulses and transient nonpulse sounds because it enables sounds of differing duration to be characterized in terms of total energy for purposes of assessing exposure risk.

The SEL metric also enables integrating sound energy across multiple exposures from sources such as seismic airguns, pile driving, and most sonar signals. Several methods exist for summing energy over multiple exposures. We use a relatively straightforward approach here, specifically

$$SEL = 10\log_{10}\left\{\frac{\sum_{n=1}^{N}\int_{0}^{T} p_n^2(t)\,dt}{(p_{ref})^2}\right\} \quad (5)\text{ eq.}$$

where instantaneous sound-pressure (p) is measured in µPa for *n* exposures and the reference pressure (p_{ref}) is 1 µPa under water and 20 µPa in air. This summation procedure essentially generates a single exposure "equivalent" value that assumes no recovery of hearing between repeated exposures. The appropriate units for underwater SEL are dB re: 1 µPa²-s, and the appropriate units for aerial SEL are dB re: (20 µPa)²-s.

Kurtosis is a statistical measure of the probability distribution of sound pressure amplitudes (Hamernik & Hsueh, 1991; Lei et al., 1994; Hamernik et al., 2003) that describes the shape of the amplitude distribution. In some regards, it appears to be a highly relevant metric in that impulsive sound with high kurtosis and high instantaneous peak pressure may be particularly injurious to some mammals (Hamernik et al., 2003). Kurtosis is related to the fourth central-moment and is defined for random variable X as

$$kurt(X) = \frac{O\left[(X-\mu)^4\right]}{\sigma^4} \quad (6)\text{ eq.}$$

where O is the expectation operator, µ is the mean, and Σ is the standard deviation. When kurtosis is high, amplitude distribution is generally more centrally peaked and may have broader tails. Normal distributions have a kurtosis value of 3 independent of the mean or standard deviation.

Frequency-selective weighting is often employed to measure (as a single number) sound pressure or energy in a specific frequency band, with emphasis or de-emphasis on particular frequencies as a function of the sensitivity to those frequencies. For aerial hearing in humans, A-weighting is derived from the inverse of the idealized 40-phon equal loudness hearing function across frequencies standardized to 0 dB at 1 kHz (Harris, 1998), providing level measures denoted as dB(A). C-weighting is determined from the inverse of the idealized 100-phon equal loudness hearing function (which differs in several regards from the 40-phon function) standardized to 0 dB at 1 kHz (Harris, 1998); level measures are denoted as dB(C).

Absent equal-loudness contours for marine mammals, special weighting functions based loosely on human weighting functions and general knowledge of functional hearing bandwidth, were developed here for the five functional marine mammal hearing groups (see the "Marine Mammal Functional Hearing Groups" section in Chapter 2). M-weighting has a mathematical structure similar to the C-weighting used in human hearing, which reflects the fact that sounds must be more intense at high and low frequencies for them to have equal auditory effect. C-weighting is most appropriate for determining the effects of intense sounds—that is, those with loudness equal to that of a tone 100 dB above threshold at 1,000 Hz. The M-weighting was designed to do much the same for the different marine mammal groups with the only difference being their varying low- and high-frequency cutoffs. The M-weighting for marine mammals, like the C-weighting used in humans, rolls off at a rate of 12 dB per octave.

The general expression for M-weighting (M[*f*]), using estimated frequency cutoffs for each functional marine mammal hearing group, is given as

$$M(f) = 20\log_{10}\frac{R(f)}{\max\{|R(f)|\}} \quad (7)\text{ eq.}$$

where

$$R(f) = \frac{f_{high}^2 f^2}{(f^2 + f_{high}^2)(f^2 + f_{low}^2)} \quad (8)\text{ eq.}$$

The estimated lower and upper "functional" hearing limits (f_{low} and f_{high}) for each of the five functional marine mammal hearing groups and the names of the frequency-weighting functions are given in Table 2. The weighting functions de-emphasize frequencies that are near the lower and upper frequency ends of the estimated hearing range as indicated by the negative relative values in Figure 1.

Audition (hearing) is a well-developed and primary sensory modality for most, if not all, marine vertebrates (Schusterman, 1981; Tyack, 1998; Fay & Popper, 2000). The vertebrate hearing system involves coding, processing, integrating, and responding to sound in a variety of ways, some not outwardly evident (Yost, 2000).

Hearing (auditory) threshold is most commonly measured by behavioral or electrophysiological responses and is defined as the SPL of the quietest sound audible in some percentage of experimental trials. In air, measurements are often conducted in specially constructed sound chambers. When that is not possible, tests must be conducted in low background noise conditions to yield meaningful threshold data.

Sensation level represents the difference (in dB) between the overall level of a sound and the receiver's auditory threshold at similar sound frequencies. It is particularly useful as a means of comparing the relative exposure level of a sound for individuals that may have different hearing capabilities. Sensation level is sometimes abbreviated SL, but this is not done in this document to avoid confusion with the very different concept of source level.

Auditory masking is the partial or complete reduction in the audibility of signals due to the presence of interfering noise (see Buus, 1997). The degree of masking depends on the spectral and temporal relationships between signals and masking noise as well as their respective RLs (e.g., Fletcher, 1940).

Sound localization is the determination of source location based on features of received sounds. This critical, complex process of the auditory system can involve the detection of sounds produced directly by a source (passive listening) or the detection of echoes reflected off a target (as in the case of biosonar).

Auditory scene analysis is the process by which the auditory system sorts out related elements of a complex acoustic environment into those arising from discrete sound sources. This process is similar to psychological processes underlying visual perception whereby many different visual images are perceived as discrete elements within a visual scene.

Temporary Threshold Shift (TTS) is a reversible elevation in hearing threshold (i.e., a non-permanent reduction in hearing sensitivity) most commonly resulting from noise exposure.

Permanent Threshold Shift (PTS) is a permanent elevation in hearing threshold (i.e., an unrecoverable reduction in hearing sensitivity). PTS can occur from a variety of causes, but it is most often the result of intense and/or repeated noise exposures. In that case it is also referred to as noise induced hearing loss (NIHL) or noise induced permanent threshold shift (NIPTS).

Courtesy: A. Friedlander

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Appendix B. Studies Involving Marine Mammal Behavioral Responses to Multiple Pulses

Low-Frequency Cetaceans/Multiple Pulses (Cell 2)

Numerous field observations have been made of low-frequency cetaceans reacting to multiple pulses, either opportunistically exposed to ongoing operations or by intentional exposures. A moderate number of species and experimental conditions have been considered, but the source was usually a seismic airgun or arrays of these intense sources. Some studies focused on migrating animals observed from fixed observation platforms or in/near migration corridors.

The general results of the severity scaling analysis for this condition suggest the onset of more significant behavioral disturbances from multiple pulses for migrating bowhead whales at RLs (RMS over pulse duration) around 120 dB re: 1 µPa (Richardson et al., 1999). For all other low-frequency cetaceans (including feeding bowhead whales), this onset was at RLs around 150 to 160 dB re: 1 µPa (Malme et al., 1983, 1984; Richardson et al., 1986; Ljungblad et al., 1988; Todd et al., 1996; McCauley et al., 1998). There is essentially no overlap in the RLs associated with the onset of behavioral responses by members of these two groups based on the information currently available.

Seismic airguns operated near bowhead whales generally initiate avoidance reactions as well as changes in locomotion and respiration (Reeves et al., 1984; Richardson et al., 1985, 1986, 1999; Ljungblad et al., 1988). During the autumn migration, avoidance behavior has been observed at relatively great (20+ km) ranges from source operations (Koski & Johnson, 1987; Richardson et al., 1999). Ljungblad et al. (1988) did not investigate behavioral reactions over such ranges. During the summer, feeding bowheads exhibited subtle behavioral responses but not active avoidance at distances beyond 6 km from airgun sources (Richardson et al., 1986; see also Miller et al., 2005).

Richardson et al. (1999) studied autumn-migrating bowhead whale and found avoidance by most individual whales at distances up to 20 km and some avoidance at 20 to 30 km. Seismic surveys using airgun arrays with 6 to 16 guns and total volumes of 560 to 1,500 in^3 were conducted in shallow (generally < 20 m) water of the Alaskan Beaufort Sea. Whales in their westward autumn migration over three seasons (1996 to 1998) were detected with aerial surveys on days with and without seismic survey activity. Using the observations of dozens of migrating whales during periods when airguns were not active, we were able to calculate the percentage of observed whales during seismic surveys that demonstrated avoidance behavior at various RLs (see Table 7). These results indicate that migrating bowhead whales in the Richardson et al. (1999) study often avoided areas where RLs exceeded 120 to 130 dB re: 1 µPa (RMS over pulse duration).

In contrast, Richardson et al. (1986) observed quite different movement patterns of bowhead whales exposed to seismic airgun sounds on their summer feeding grounds in the Canadian Beaufort Sea. Received levels from a single seismic airgun (0.66-L) were measured *in situ* near individual whales being observed 3 to 5 km from the sound source, and ranged from 118 to 133 dB re: 1 µPa. Visual orientation by groups of whales during airgun exposure was observed on two of five occasions; only minor changes in swimming and respiration patterns were observed. Richardson et al. (1986) also made opportunistic observations of groups of bowhead whales near a seismic vessel operating an airgun array. At the highest RLs, some measurements exceeded the dynamic range of the recording equipment and are considered exposure minima, although this was not the case for most measurements relevant to the behavioral observations. From these observations and the controlled exposure to sounds from a single airgun, Richardson et al. (1986) concluded that some whales responded subtly by changing diving and breathing patterns at relatively low RLs (*ca.* 120 to 140 dB re: 1 µPa), but that avoidance and other more profound behavioral changes were generally not observed unless the RL was ≥ 160 dB re: 1 µPa.

Ljungblad et al. (1988) conducted a series of acoustic experiments on behavioral reactions of bowhead whales exposed to sounds from ships with operating airgun(s). Experiment 1 was conducted on a group of eight whales. When a seismic vessel approached to within 3.5 km (max. RL near observed individuals was 142 dB re: 1 µPa), the bowhead whales coalesced and moved in a tight group away from the approaching vessel.

Experiment 2 involved a group of three bowhead whales that demonstrated startle responses at the onset of sounds from an airgun 7 km away (max. measured RL was 165 dB re: 1 μPa). Behavior returned to pre-exposure values shortly after the operation was terminated. Experiment 3 involved a group of seven bowhead whales that demonstrated avoidance behavior at ranges of ~3.5 km (max. measured RL of 178 dB re: 1 μPa). Experiment 4 involved a group of 50 bowhead whales. Behavioral reactions were first observed at ranges of about 8 km (max. measured RLs of 157 dB re: 1 μPa) and avoidance behavior was noted at ~3 km (RLs ~165 dB re: 1 μPa). Avoidance behavior in this instance similarly abated shortly following cessation of exposure (and was thus assigned a behavioral score of 6).

Recent work on summering bowhead whales by Miller et al. (2005) also found that avoidance responses were limited to distances of at most a few kilometers and RLs exceeding 160 dB re: 1 μPa. Miller et al. conducted a monitoring program over two summers for various marine mammals offshore of the Mackenzie Delta in the Southeast Beaufort Sea before and during seismic surveys. They presented observational data from both vessel-based and aerial observations of bowhead whales, belugas, and several pinniped species. The general methodology is briefly discussed here as well as data on behavioral responses by low-frequency cetaceans (bowhead whales) and the corresponding rank on the severity scale. The airgun operations involved 3-D seismic profiling from a 67-m vessel using two identical 2,250 in^3 sleevegun arrays, each with 24 airguns. Shots were at 8-s intervals and at a depth of 5 m below the surface of the water. Surveys were conducted in very shallow water (13 m average). Acoustic monitoring with calibrated hydrophones across the 10 Hz to 24 kHz bandwidth was conducted while seismic operations were underway. Physical properties of the operational environment, and hence sound propagation in the shallow water environments, were highly variable, but RLs as a function of range from active airgun arrays were measured. Vessel-based observers and aerial surveyors used line-transect methods to monitor marine mammals in and adjacent to seismic operational areas, both before and during shooting. Bowhead whales observed during the periods coincident with seismic operations were presumed to be feeding (i.e., not migrating). Many bowheads (355 individuals in 232 groups) were seen by marine mammal observers aboard the seismic vessel. Sighting rates were lower and mean sighting distances were somewhat larger during seismic operations than at times when the airguns were not operating, but the zone of avoidance around active airguns was very limited. The approximate difference in mean sighting distance was ~600 m. Similarly, the aerial surveyors did not detect any large-scale avoidance of the airgun operations by bowheads. These observations were generally consistent for both years in which measurements were made and are generally consistent with the observations of Richardson et al. (1986) in the same region and season (summer). Animals not exhibiting observable behavioral reactions (response score: 0) were consistently sighted in areas where RLs very likely ranged from 130 to 180 dB re: 1 μPa. The general lack of sightings within a small area around the seismic vessel suggests behavioral avoidance (response score: 6) at RLs exceeding 180 dB re: 1 μPa. Exposures were not estimated to exceed 190 dB re: 1 μPa. The entire study was treated as a single observation for the purposes of the behavioral analysis. Half of the "observation" was scored as avoidance behavior and half as no response, with exposure RL bins from 130 to 190 dB re: 1 μPa (Table 6).

The combined data for bowhead whale avoidance of airgun sounds (Richardson et al., 1986, 1999; Ljungblad et al., 1988; Miller et al., 2005) indicated that, when migrating, these animals can be particularly prone to behavioral disturbance, with the onset of significant responses occurring at approximately 120 dB re: 1 μPa (RMS over pulse duration) (Table 6). In contrast, when feeding, they may show subtle effects at low RLs but only tend to display active avoidance at RLs exceeding 160 dB re: 1 μPa.

Low-frequency cetaceans, other than migrating bowhead whales, appear to be much more tolerant of exposure to multiple pulses, although data are limited to a few species and (primarily) airgun sources. Available data for species other than bowheads include reactions to opportunistic and intentional exposures of humpback whales (Malme et al., 1985; Todd et al., 1996; McCauley et al., 1998, 2000) and gray whales (Malme et al., 1983, 1984, 1986, 1988; also see review by Moore & Clarke, 2002). Todd et al. (1996), Malme et al. (1983, 1984), and McCauley et al. (1998) are included in the behavioral scoring analysis here because they contain sufficient information on exposures and individual responses of low-frequency cetaceans other than bowhead whales.

Todd et al. (1996) analyzed the impact of construction activity (explosions and drilling) on the entanglement of three foraging humpback whales off Newfoundland. They conducted observations of whale behavior during and following explosions and obtained acoustic measurements of underwater sound signatures. The data suggest few short-term changes in movement and behavior patterns in response to discrete exposures;

however, repeated exposures to high levels may have resulted in sensory impairment in whales and perhaps greater susceptibility to entanglement in fishing gear.

Malme et al. (1983, 1984) documented behavioral reactions of migrating gray whales to seismic pulses from both single airguns and an array. Only land-based observers were used, which meant that the observers could not have affected the whales' behavior. Both phases of the investigation yielded the general conclusion that RLs exceeding 160 dB re: 1 μPa (on an approximate RMS basis) were required to cause migrating gray whales to avoid airgun sounds, although statistically significant reactions that were less profound occurred at much larger ranges and lower levels. From their empirical phase II results, Malme et al. (1984) calculated 10, 50, and 90% probabilities of gray whale avoidance reactions in these conditions to be 164, 170, and 180 dB re: 1 μPa, respectively.

McCauley et al. (1998) made behavioral observations of migrating humpback whales off western Australia during seismic operations with a single airgun and several airgun array configurations. Seismic track lines were oriented perpendicular to the migration paths of humpback whales moving through the area. Aerial surveys were conducted to determine the presence of humpback whales moving through the survey area. Detailed observational data were presented for individuals and groups of whales; RLs were measured at variable ranges. The seismic survey did not appear to grossly affect the migration of humpback whales through the area; however, avoidance behavior was observed to begin at ranges from 5 to 8 km and to be almost universal at ranges of 1 to 4 km. Exposures to a single airgun (20 in^3) were extrapolated to equivalent ranges for exposure to full arrays based on empirical measurements. The data indicated an onset of behavioral avoidance at ~159 dB re: 1 μPa (peak-to-peak), roughly equivalent to the full array at 5 km. General behavioral avoidance (most individuals) occurred at a range of about 1 km for the single gun (~168 dB re: 1 μPa [peak-to-peak]), equivalent to the full array at about 3 km. Some individual whales did approach closer than the typical 3-km stand-off range; these may have been males investigating the presence of the low-frequency source.

In addition to presenting again the results given in the McCauley et al. (1998) paper, McCauley et al. (2000) provide additional behavioral observations of 16 humpback whale pods that approached as a single airgun (Bolt PAR 600b 20-in^3) was operated. These whales were also observed after termination of airgun operations. These trials were conducted in a large embayment (Exmouth Gulf) as the animals were engaged in a variety of resting and social behaviors. Five trials were excluded from consideration in our analysis, but behavioral observations were reported for the remaining 11. Of these, ten included cow pods of various sizes, and one was a lone male. Since the cow pods were not migrating and were not individually identified, a single behavioral observation is included in Table 7 for the ten observations. The results for the cow pods were very consistent, indicating clear avoidance (severity score = 6) of the airgun at exposures in the 140 to 150 dB re: 1 μPa range (RMS over pulse duration). The lone male essentially ignored the airgun until within *ca.* 100 m, when the received level approached 180 dB re: 1 μPa (RMS); this response may have had as much or more to do with the presence of the vessel than exposure to the airgun sound. Noting this contextual complexity here, a single observation for this individual is reported in the 170 to 180 dB re: 1 μPa exposure bin in Table 7 as general avoidance (severity score = 6).

Mid-Frequency Cetaceans/Multiple Pulses (Cell 5)

A limited number of behavioral observations have been made of mid-frequency cetaceans exposed to multiple pulses. Field observations have involved sperm whales and a few other odontocete species exposed to seismic airguns and small explosives (Madsen & Møhl, 2000; Madsen et al., 2002; Miller et al., 2005). Laboratory investigations have considered behavioral responses to various kinds of multiple pulse sources (Akamatsu et al., 1993). As in most criteria cells, a number of reported observations were not scored and reported here due to lack of relevant information and difficulties in accounting for various contextual variables. A summary of those studies used and others considered is given in Table 8; the severity scaling analysis for Cell 5 is shown in Table 9.

The combined data for mid-frequency cetaceans exposed to multiple pulses do not indicate a clear pattern of increasing probability and severity of response with increasing RLs. In certain conditions, multiple pulses at relatively low RLs (~80 to 90 dB re: 1 μPa) temporarily silence individual acoustic behavior for one species (sperm whales). In other cases with slightly different stimuli, RLs in the 120 to 180 dB re: 1 μPa range failed to elicit observable reactions from a significant percentage of individuals of the same species, both in the field and in the laboratory.

Field Observations (Cell 5)

Madsen & Møhl (2000) investigated sperm whale responses to small underwater detonators that included 1-g TNT charges, producing a 1-ms broadband (300 Hz to 15 kHz) pulse; several charges were triggered per day. Echolocation click behavior was monitored, and one whale was localized acoustically. This individual demonstrated no modulation of vocal behavior when exposed to an RMS-equivalent RL of ~173 dB re: 1 µPa. There was also one observation of a whale exposed to 179 dB re: 1 µPa; it continued breathing normally with no visible response.

Madsen et al. (2002) studied responses of sperm whales in Norway to sounds associated with distant seismic survey operations. Calibrated RLs for individuals and correlated acoustic behavior are reported for three discrete sightings over a 5-d period. The first observation involved three sperm whales tracked by acoustic localization within a dispersed array of calibrated hydrophones, which also recorded airgun sounds from an array operating 40 km away. RL at the position of the whale was estimated to be 123 dB re: 1 µPa. The second observation (3 d later) involved a single sperm whale recorded before, during, and after airgun exposure at a range of 86 km; measured RL was 130 dB re: 1 µPa. The third observation (2 d later) involved three individuals; the survey vessel was 94 km away and measured RL was 130 dB re: 1 µPa. No change in sperm whale acoustic behavior was noted in any of these cases. The authors also played artificial codas and noticed that two whales directed their sonar beams at the speaker, but insufficient information is given to associate this response with a particular RL.

Miller et al. (2005) documented behavioral reactions of various marine mammal species, including belugas, to airgun operations. The general methodology is detailed above (see the "Cell 2" section). Owing to their normal seasonal patterns in the Beaufort Sea, belugas were most abundant in the Miller et al. (2005) study area prior to the start of seismic operations. There were relatively few vessel-based sightings, most of which were made when airguns were not active. Many belugas were observed during aerial surveys, however, and these data were used to compare beluga sightings within concentric 10-km bands around the active seismic source with sighting rates in non-airgun conditions. During airgun operations, Miller et al. detected significantly fewer animals 10 to 20 km from seismic operations and an unexpectedly high number of sightings in the 20- to 30-km zone. This was suggestive of behavioral avoidance of seismic operations at distances up to 20 km. These observations may in part explain why so few animals were observed by shipboard marine mammal observers. Miller et al. noted that the apparent avoidance of seismic operations was much greater than expected if the whales were responding to non-airgun sounds associated with vessel operation. For the purposes of our behavioral analyses, the combined beluga results were treated as a single observation that was subdivided equally into either avoidance behavior or no observable response. Belugas exposed to RLs of 100 to 120 dB re: 1 µPa (RMS over pulse duration) were determined to have had no observable reaction (response score: 0) to seismic exposures. RLs between 120 and 150 dB re: 1 µPa were determined to have induced temporary avoidance behavior (response score: 6) in belugas, based on the vessel-based and aerial observations. Based on both the vessel-based and aerial surveys, exposures apparently did not exceed 150 dB re: 1 µPa. Weighted behavioral response scores for each of these five exposure RL bins are given in Table 7.

Several studies involved behavioral reactions of free-ranging, mid-frequency cetaceans but lacked specific measures to be included directly in our analyses. André et al. (1997) exposed sperm whales to various stimuli, including two pulse sounds (recorded coda playbacks and a 10-kHz pulse). A significant number of exposed whales exhibited vocal modulations and modified diving behavior, but insufficient information is available on received exposures of individual whales. Stone (2003) compiled a large database of sighting data of several mid-frequency cetacean species observed from seismic survey vessels. Sighting rates of small odontocetes were significantly lower when airguns were firing, and they were sighted at greater distances from vessels, indicating avoidance behavior. The study sponsors (JNCC) kindly provided raw data for use in our quantitative avoidance analyses, but they are not included due to difficulties in estimating exposure RL for individual sightings. (See also Stone & Tasker, 2006, for a recently published account.)

Laboratory Observations (Cell 5)

Akamatsu et al. (1993) investigated avoidance behavior in two captive false killer whales exposed to 15 different kinds of sounds, including pulse sequences (manual strikes on a metal pipe once every 2 s) in the 24 to 115 kHz range. For this stimulus, no avoidance was seen following the first exposure (174 dB re: 1 µPa), but temporary avoidance behavior (response score: 6) was observed for successive exposures at 174 and 178 dB re: 1 µPa.

Finneran et al. (2000) observed behavioral responses of two captive bottlenose dolphins and a beluga whale during TTS experiments involving a series of impulsive exposures designed to replicate distant explosions. Each animal exhibited alterations of nominal trained behaviors (reluctance to return to experimental stations) during the experiment; the onset of behavioral disturbance occurred in the beluga at 220 dB re: 1 μPa (peak-to-peak) and in the two bottlenose dolphins at 196 and 209 dB re: 1 μPa (peak-to-peak), respectively. In a related study, Finneran et al. (2002b) observed behavioral responses of a bottlenose dolphin and a beluga whale after exposure to impulsive sounds produced by a water gun. Both individuals showed a similar reluctance to return to experimental stations (beluga at 202 dB re: 1 μPa (peak-to-peak); bottlenose dolphin at 229 dB re: 1 μPa [peak-to-peak]). Romano et al. (2004) studied physiological responses to these exposures in these same animals. They observed clear neuro-immune responses in the beluga at exposures above 222 dB re: 1 μPa (peak-to-peak) and significant differences in aldosterone and monocyte counts in the dolphin for exposures exceeding 225 dB re: 1 μPa (peak-to-peak).

High-Frequency Cetaceans/Multiple Pulses (Cell 8)

Based on our source type distinction (see Chapter 2), virtually all sound sources used in behavioral studies of high-frequency cetaceans (e.g., acoustic harassment devices [AHDs] and acoustic deterrent devices [ADDs]) would be characterized as nonpulses. While individual elements produced by some of these sources would be characterized as pulses, and sequences of them as multiple pulses, they are generally emitted in such rapid fashion that mammalian auditory systems are likely to perceive them as nonpulses. Further, some AHDs, ADDs, and all other sources used in behavioral studies with high-frequency cetaceans lack the characteristics of pulses. Due to the lack of data, it is not possible to present any behavioral response data on multiple pulses for high-frequency cetaceans; available data for nonpulse sounds are considered elsewhere (see the "High-Frequency Cetaceans/Nonpulses [Cell 9]" sections of Chapter 4 and Appendix C). We note the need for behavioral research on these animals using sound sources unequivocally classified as pulses.

Pinnipeds in Water/Multiple Pulses (Cell 11)

Information on behavioral reactions of pinnipeds in water to multiple pulses is derived from studies using small explosives similar to those used in fisheries interactions, construction activity, and seismic surveys. Several studies lacked matched data on acoustic exposures and behavioral responses by individuals. As a result, the quantitative information on reactions of pinnipeds in water to multiple pulses is very limited. Our general finding is that exposures in the ~150 to 180 dB re: 1 μPa range (RMS over pulse duration) generally have limited potential to induce avoidance behavior in pinnipeds, whereas RLs exceeding 190 dB re: 1 μPa are likely to elicit responses, at least in some ringed seals (Harris et al., 2001; Blackwell et al., 2004b; Miller et al., 2005).

Harris et al. (2001) documented responses of pinnipeds (primarily ringed seals, but a few bearded and spotted seals) and obtained calibrated measures of RLs within defined spatial zones during operation of a single airgun, an 11-airgun array totaling 1,320 in^3, and during control periods. Visual observations from the seismic vessel were limited to the area within a few hundred meters, and 79% of the seals observed were within 250 m of the vessel. During daylight, seals were observed at nearly identical rates with no airguns, one airgun, or when a full airgun array was firing. Seals were significantly further away during full array operations compared to the other two conditions. Also, there was some avoidance within 150 m of the vessel in these conditions (0.37 seals seen per hour in control periods compared to 0.21 seals/h during full array operations). Seismic operations were not believed to cause many, if any, seals to desert the operational area.

Blackwell et al. (2004b) investigated behavioral reactions of ringed seals to impact sounds associated with the driving of steel pipes in the construction of an oil production facility. Multiple strikes were recorded under water at distances up to 3 km from the source. Unweighted peak pressure level, SPL, and SEL measurements were made at various distances. At the closest point (63 m), RLs were 151 dB re: 1 μPa (RMS), 157 dB re: 1 μPa (peak), and 145 dB re: 1 μPa^2-s (SEL). Pulses had measurable components extending to over 10 kHz, although more than 95% of the energy in the signals was below 225 Hz. A frequency-weighting metric somewhat similar to that proposed here was applied to the recorded signals in estimating audibility ranges. Individuals demonstrated no or low-level behavioral responses to pile-driving sounds, but were somewhat responsive to helicopter overflights. Blackwell et al. noted, however, that their data were collected after a prolonged period of intensive construction activity and may reflect the least responsive part of the original population of seals that may have already habituated to the noise source. Individual observations in which helicopters were not present are considered in our behavioral analysis, weighted by the total number of relevant observations (Table 11). Aerial measurements of multiple pulse exposures were also obtained in this study and are considered in the relevant condition below.

Miller et al. (2005) documented behavioral reactions of various marine mammal species, including pinnipeds in water, to seismic airgun operations. The general methodology is detailed above (see the "Cell 2" section). The vast majority (> 90%) of the seals were ringed seals and the remainder were bearded seals. Vessel-based observers saw seals around the vessel, and often quite close to it, throughout the period of seismic operations. Seals were observed significantly further away during airgun operations in the first summer, whereas the reverse pattern was actually the case in the second season. Combined, the results suggest essentially no observable behavioral response in pinnipeds exposed to seismic signals in these specific conditions. Based on the acoustic measurements that were conducted and the areas in which these pinnipeds were observed, RLs were likely 170 to 200 dB re: 1 µPa (RMS over pulse duration). A single observation of no reaction (response score: 0) for pinnipeds in water is reported for this study and is weighted equally across these exposure RL bins (Table 8).

Several other studies were deleted from our analysis due to a lack of certain information. Two studies investigated small firecracker-like explosives (called "seal bombs") and their effect on the underwater behavior of pinnipeds around fishing gear (Shaughnessy et al., 1981; Mate & Harvey, 1987). Initially, these explosives tend to induce the desired avoidance behavior, but this response fades quickly due to habituation (see Richardson et al., 1995). Mate & Harvey (1987) reported fairly extensive descriptions of startle and temporary avoidance data as well as some information on exposure conditions. Besides the challenging matter of interpreting the apparently rapid habituation to this sound source, however, data are lacking that relate discrete exposures with defined behavioral responses of specific individual pinnipeds. For these reasons, we excluded data on responses to seal bombs from our analysis. Moulton et al. (2003, 2005) conducted surveys of ringed seal distribution before and during the construction and operation of the same oil production facility described by Blackwell et al. (2004a, 2004b). Sound sources included nonpulse as well as multiple pulse sources (including impact pile-driving). Their observations across multiple seasons indicated little or no behavioral avoidance of the area in response to various industrial activities. Due to difficulties with control observations across seasons and the lack of information about discrete exposures and individual reactions, however, we excluded the Moulton et al. (2003, 2005) data from our analysis. A final study for which available data were insufficient for inclusion here is Thompson et al. (1998). That telemetry study seemed to show much higher responsiveness of gray and harbor seals to airgun sounds than has been demonstrated in other studies, which relied on visual observations. Thus, future studies may show some seals to be more responsive to multiple pulses than Table 11 would suggest.

Pinnipeds in Air/Multiple Pulses (Cell 11)

The effects of multiple aerial pulses on pinnipeds are among the least well-documented of the conditions we considered. Most of the available data on responses to pulses are from single-pulse events (e.g., rocket launches) over populations of pinnipeds exposed to such signals repeatedly (e.g., Thorson et al., 1998, 1999, 2000a, 2000b; Berg et al., 2001, 2002, 2004). These launches are not repeated so frequently that the exposure can be considered as involving multiple pulses, and many of the exposures include nonpulse components. However, they are discussed in some detail in this appendix (as well as in Appendix C for nonpulses within these studies) along with several other studies potentially relevant to Cell 14 but ultimately not used in the analysis here. Consequently, the quantitative information analyzed for reactions of pinnipeds in air exposed to multiple pulses (see Table 12 for summary and Table 13 for severity scaling analysis) focuses on the aerial data of Blackwell et al. (2004b). These extremely limited data suggest very minor, if any, observable behavioral responses for exposures ranging from 60 to 80 dB re: 20 µPa.

Blackwell et al. (2004b) reported behavioral reactions of ringed seals to aerial impact sounds from pile-driving (described above). Multiple strikes were recorded in air at distances up to 500 m from the source. Unweighted SPL, peak sound pressure levels, and SEL measurements were made at various distances. At the closest point (63 m) average RLs were 93 dB re: 20 µPa (RMS), 111 dB re: 20 µPa (peak), and 87 dB re: $(20\ \mu\text{Pa})^2$-s (SEL). Mean pulse durations were between 0.17 and 0.63 s, with measurable energy to over 10 kHz, but with 95% of the energy occurring between 89 and 3,534 Hz. A frequency-weighting metric somewhat similar to that proposed here was applied to the recorded signals in estimating audibility ranges. Individuals demonstrated very limited behavioral responses to pile-driving sounds in some conditions (most appeared either "indifferent or curious") but were more responsive to helicopter overflights. Data were collected after prolonged construction activities, and some habituation probably had taken place already. Individual observations for which helicopters were not present are considered in the behavioral analysis here and weighted by the total number of relevant observations (Table 13) to equal a single observation for the study.

Perry et al. (2002) measured the effects of repeated (0 to 5/d) sonic booms from Concorde aircraft on harbor and gray seals on Sable Island, Nova Scotia. They measured the number of animals on shore before and after booms as well as the frequency of various behaviors. Additionally, they compared heart rates in exposure and control conditions using recording devices deployed on the animals. They reported received sound overpressure of booms on the breeding beaches of both pinniped species. Observed effects on animal presence, behavior, and heart rate were generally minor and not statistically significant; animals were largely tolerant of the sounds but became somewhat more alert following them. However, Perry et al. (2002) note that there is a long history of sonic booms from aircraft in the area and the animals are likely habituated to their presence. Due to this complication and the lack of explicit received SPL measures at exposed individuals, we did not score the results of Perry et al. (2002) here.

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Appendix C. Studies Involving Marine Mammal Behavioral Responses to Nonpulses

Low-Frequency Cetaceans/Nonpulses (Cell 3)

While there are clearly major areas of uncertainty remaining, there has been relatively extensive behavioral observation of low-frequency cetaceans exposed to nonpulse sources. As summarized in Table 14, these field observations involve the majority of low-frequency cetacean species exposed to a wide range of industrial, active sonar, and tomographic research active sources (Baker et al., 1982; Malme et al., 1983, 1984, 1986; Richardson et al., 1990b; McCauley et al., 1996; Frankel & Clark, 1998; Borggaard et al., 1999; Biassoni et al., 2000; Croll et al., 2001; Palka & Hammond, 2001; Nowacek et al., 2004). Observations from several related studies (Dahlheim, 1987; Frankel & Clark, 2000, 2002; Schick & Urban, 2000; Moore & Clarke, 2002; Jahoda et al., 2003; Mobley, 2005) were reviewed briefly but not analyzed here because key information was lacking.

These papers generally indicate no (or very limited) responses at RLs 90 to 120 dB re: 1 μPa and an increasing probability of avoidance and other behavioral effects in the 120 to 160 dB re: 1 μPa range (Table 14). However, the data also indicate considerable variability in RLs associated with behavioral responses. Contextual variables (e.g., source proximity, novelty, operational features) appear to have been at least as important as exposure level in predicting response type and magnitude.

Baker et al. (1982) investigated behavioral responses of individual humpback whales to vessel traffic in southeast Alaska. Individual RLs were not reported, but sufficient information regarding individual ranges was obtained to approximate exposures given that the acoustic characteristics of identical classes of vessel classes involved were measured in similar conditions by Miles & Malme (1983). Results indicate some behavioral avoidance when RL was in the 110 to 120 dB re: 1 μPa range and clear avoidance at 120 to 140 dB re: 1 μPa.

Malme et al. (1983, 1984) used playback methods to document behavioral reactions of migrating gray whales to intermittent sounds of helicopter overflights and continuous sounds from drilling rigs and platforms. Both phases of the investigation yielded the general conclusion that RLs exceeding 120 dB re: 1 μPa induced demonstrable behavioral reactions (avoidance). Malme et al. (1984) calculated 10%, 50%, and 90% probabilities of gray whale avoidance reactions in these conditions as 110, 120, and 130 dB re: 1 μPa. Malme et al. (1986) observed the behavior of feeding gray whales during four experimental playbacks of drilling sounds (50 to 315 Hz; 21-min overall duration and 10% duty cycle; source levels 156 to 162 dB re: 1 μPa-m). In two cases for RLs 100 to 110 dB re: 1 μPa, there was no observed behavioral reaction. Avoidance behavior was observed in two cases where RLs were 110 to 120 dB re: 1 μPa.

Richardson et al. (1990b) performed 12 playback experiments in which bowhead whales in the Alaskan Arctic were exposed to drilling sounds. Low-frequency source characteristics and transmission loss were well-characterized, enabling RL estimates to be made for individual cases. Whales generally did not respond to exposures in the 100 to 130 dB re: 1 μPa range, although there was some indication of minor behavioral changes in several instances.

Using different detection and sampling techniques, McCauley et al. (1996) reported several cases of humpback whales responding to vessels in Hervey Bay, Australia, along with measurements of noise RL. Not all cases reported provided sufficient information to associate a response or lack of response with exposure, but in three cases, individual responses and noise RL were reported. Results indicated clear avoidance at RLs between 118 to 124 dB re: 1 μPa.

Palka & Hammond (2001) analyzed line transect census data in which the orientation and distance off transect line were reported for large numbers of minke whales. General additive models were used to estimate the range at which cetaceans respond to the noise of the research vessel by approach or avoidance. The typical avoidance distance for 272 minke whales in the Gulf of Maine was 717 m; for 352 minke whales in the North Sea, it was 563 m; and for 493 minke whales in the Northeastern Atlantic, it was 695 m. Received levels were estimated based on a nominal source level for that class of research vessel (*ca.* 170 to 175 dB re: 1 μPa-m) and an assumption of spherical (20 log R) spreading loss (54 dB loss @ 500 m; likely reasonable for these conditions). These data are represented in Table 14 by the 110 to 120 dB re: 1 µPa exposures and a relatively low (less severe) behavioral response score of three (i.e., minor changes in locomotion speed, direction, and/or diving profile).

Several additional studies have used playback experiments with active sound sources to investigate the behavioral reactions of low-frequency cetaceans to nonpulse sources. Biassoni et al. (2000) and Miller et al. (2000) report behavioral observations for humpback whales exposed to a low-frequency sonar stimulus (160- to 330-Hz frequency band; 42-s tonal signal repeated every 6 min; source levels 170 to 200 dB re: 1 µPa-m). Measured RLs ranged from 120 to 150 dB re: 1 µPa. In nine cases, individual whales continued singing throughout exposures, while in four instances, individuals ceased calling when they joined another whale. The cessation of song and joining another individual is typical of normal mysticete social interactions (Tyack, 1981). Consequently, these events were not scored as a vocal response to the playback but as a moderate orienting behavior (severity score = 2). For the remaining five playbacks, individual whales stopped singing during exposure without joining other whales (severity scale = 4). Although singers also stop spontaneously under control conditions, the latter five experimental trials were considered vocal cessation resulting from sound exposure (Biassoni et al., 2000). However, there are insufficient data to compare control and experimental cases for spontaneous rates of cessation. Analysis of all singers indicated an increase in song duration during exposure due to increased repetition of elements of the song. Since it was possible that some individual whales were represented multiple times within the playbacks, the Biassoni et al. (2000) and Miller et al. (2000) data were scored as a single behavioral observation. The 18 individual observations were weighed inversely by the total number (1/18) in Table 15.

Croll et al. (2001) investigated responses of foraging fin and blue whales to the same LFA sonar stimulus off southern California. Unlike the previous two studies, where individual experimental subjects were tracked on a behavioral scale, this study used sighting data on an ecological scale. Playbacks and control intervals with no transmission were used to investigate behavior and distribution on time scales of several weeks and spatial scales of tens of kilometers. Sightings and whale diving behavior were not random but were related to environmental features such as the continental shelf break and its effects on prey abundance rather than operation and location of the nonpulse sonar source. The general conclusion was that whales remained feeding within a region for which 12 to 30% of exposures exceeded 140 dB re: 1 µPa. A single observation was scored for this study because individual responses were not reported.

Frankel & Clark (1998) conducted playback experiments with wintering humpback whales around the Big Island of Hawai'i. The sound source was a single speaker producing a low-frequency "M-sequence" (sine wave with multiple-phase reversals) signal in the 60 to 90 Hz band. This was similar in bandwidth to the ATOC source, but had a much lower output level (172 dB re: 1 µPa @ 1 m). A vertical line array of calibrated hydrophones was deployed from a spar buoy to measure received signals *in situ*. Detailed observations of many behavioral patterns (including respiration, diving, and general movements) were recorded before, during, and after playback ($n = 50$) and control ($n = 34$) sequences. A single trial also involved playback of humpback foraging sounds. Most of the playback sequences involved very low-level RLs, *ca.* 90 to 120 dB re: 1 µPa, though not specified in sufficient detail to include in the analysis here. For 11 playbacks, exposures were between 120 and 130 dB re: 1 µPa and included sufficient information regarding individual responses. During eight of the trials, there were no measurable differences in tracks or bearings relative to control conditions, whereas on three occasions, whales either moved slightly away from ($n = 1$) or towards ($n = 2$) the playback speaker during exposure. Because it was not possible to determine whether the same individual whales were represented more than once in the playback sequences, a single observation was recorded for Frankel & Clark (1998), with 0.73 of this observation (8/11) scored as a 0 (no response) and 0.27 (3/11) scored as a 3 (minor changes in locomotion speed, direction, and/or diving). A final important observation from the detailed statistical analysis by Frankel & Clark was that the presence of the source vessel itself had a greater effect than did the M-sequence playback.

Finally, Nowacek et al. (2004) used controlled exposures to demonstrate behavioral reactions of northern right whales to various nonpulse sounds. Playback stimuli included ship noise; social sounds of conspecifics; and a complex, 18-min "alert" sound consisting of repetitions of three different artificial signals (alternating 1-s pure tones [500 and 850 Hz]; a 2-s, tonal, frequency downsweep [4,500 to 500 Hz]; and a pair of 1-s pure tones [1,500 Hz and 2,000 Hz] amplitude modulated at 120 Hz). A total of ten whales were tagged with calibrated instruments that measured received sound characteristics and concurrent animal movements in three dimensions. Five out of six exposed whales reacted strongly to alert signals at measured RLs between 130 and 150 dB re: 1 µPa (i.e., ceased foraging and swam rapidly to the surface; severity scale = 7). Two of these individuals were not exposed to ship noise and are given as a discrete observation in Table 15, whereas the other four were exposed to both stimuli and thus weighted as 0.5 (1/2) observations for the respective RL and severity score. These whales reacted mildly to conspecific signals (not scored here because of biological signals). Seven whales, including the four exposed to the alert stimulus, had no measurable response to either ship sounds or actual vessel noise. This study by Nowacek et al. included the careful experimental design, controls, and detailed information on exposure and individual behavioral response that were required for behavioral analysis. More studies of this type and rigor are urgently needed (see Chapter 5).

We reviewed additional studies concerning low-frequency cetaceans and nonpulse sounds but did not include them in the analysis here, generally due to the absence of key information. Dahlheim (1987) exposed gray whales to playbacks of outboard noise, gray whale calls, and tonal sounds. Whales significantly increased calling rate and modified call structure for sources other than the test tone (the latter caused all vocalization to cease). During and following longer duration playbacks of oil drilling and killer whale sounds with more precise tracking of gray whale locations, individuals spent more time milling, and whales remained farther offshore during killer whale playbacks. Unfortunately, insufficient information is presented to associate changes with specific RLs. Borggaard et al. (1999) measured the effects of industrial activity on several mysticete species in Newfoundland, but insufficient information is reported on individually discernible responses. Schick & Urban (2000) applied statistical methods to assess spatial avoidance of active drilling rigs by bowhead whales, but no acoustic data are reported. Moore & Clarke (2002) synthesized previously published data (all considered separately above) on numerous nonpulse sources, in order to assess the avoidance probability of gray whales for various exposure RLs. Jahoda et al. (2003) studied individual responses of fin whales ($n = 25$) to close rapid approaches of small vessels; 18 observations included control and experimental data. Clear behavioral responses were observed, but neither RL nor range from source to individuals were given. Results are further complicated by whale tagging attempts from the vessel. Frankel & Clark (2000) and Mobley (2005) investigated the distribution of humpback whales in Hawai'i in relation to the operation of a low-frequency tomographic source (*ca.* 75 Hz; 37.5-Hz nominal bandwidth; 20-min duration every 2 h during daylight hours; source level: 195 dB re: 1 µPa-m). Frankel & Clark (2000) observed whales from a land station and determined that the average distance between the sound source and the whale groups sighted was significantly greater during source operation. These and other data were also considered in the context of other factors affecting humpback whale distribution off the island of Kaua'i. Mobley (2005) conducted aerial surveys in each of three years (2001, source off; 2002 & 2003, source on) during the peak season of humpback residency. Abundance and distribution of whales were very similar in the area surrounding the source over all three years; small differences in sighting rates, sighting location depth, and distances from the source and shore were not statistically significant. Frankel & Clark (2002) and Mobley (2005) lack explicit data on RLs associated with individual behavioral observations, which precludes their inclusion here.

Mid-Frequency Cetaceans/Nonpulses (Cell 6)

A relatively large number of mid-frequency cetaceans have been observed in the field and in the laboratory responding to nonpulse sounds, including vessels and watercraft (LGL & Greeneridge, 1986; Gordon et al., 1992; Palka & Hammond, 2001; Buckstaff, 2004; Morisaka et al., 2005), pulsed pingers and ADD/AHDs (Watkins & Schevill, 1975; Morton & Symonds, 2002; Monteiro-Neto et al., 2004), industrial activities (Awbrey & Stewart, 1983; Richardson et al., 1990b), mid-frequency active military sonar (NRL, 2004a, 2004b; NMFS, 2005), and tones or bands of noise in laboratory conditions (Nachtigall et al., 2003; Finneran & Schlundt, 2004). Summary information on these studies is given in Table 16. As in other conditions, a number of potentially relevant field studies are not included in the severity scaling analysis due to lack of sufficiently detailed information.

An additional challenge in interpreting many of the field data for this condition is isolating the effect of RL from the effects of mere source presence (as possibly indicated by visual stimuli or other aspects of acoustic exposure such as the presence of high-frequency components) and other contextual variables. For this reason, several studies were considered but not integrated into the analysis.

The laboratory observations are of captive cetaceans exposed to precisely controlled and known noise exposures in the context of hearing and TTS experiments. The relevance of behavioral reactions of trained, food-reinforced captive animals exposed to noise in assessing reactions of free-ranging marine mammals is not well-known, however (discussed below).

The combined field and laboratory data for mid-frequency cetaceans exposed to nonpulse sounds do not lead us to a clear conclusion about

RLs coincident with various behavioral responses (see severity scaling, Table 17). In some settings, individuals in the field showed profound (and what we regard here as significant) behavioral responses to exposures from 90 to 120 dB re: 1 µPa, while others failed to exhibit such responses for exposure RLs from 120 to 150 dB re: 1 µPa. Contextual variables other than exposure RL, and probable species differences, are the likely reasons for this variability. Context, including the fact that captive subjects were often directly reinforced with food for tolerating noise exposure, may also explain why there is great disparity in results from field and laboratory conditions—exposures in captive settings generally exceeded 170 dB re: 1 µPa before inducing behavioral responses.

Field Observations (Cell 6)

The most extensive series of observations regarding vessels and watercraft is from LGL and Greeneridge (1986) and Finley et al. (1990), who documented belugas and narwhals (*Monodon monoceros*) congregated near ice edges reacting to the approach and passage of ice-breaking ships. Over a 3-y period (1982 to 1984), they used both ice-based local observations of whales and aerial surveys, and also made detailed acoustic measurements. The survey method made it difficult to assess independent groups of animals. Some large-scale groupings could be identified for several different "disturbance" periods, however. Pre-disturbance group size was ~3; we divided reported numbers of disturbed "herds" by three to estimate the number of independent groups. Aerial surveys in 1984 lumped sightings by minute, which corresponded to about 3.4 km in distance. We considered this distance sufficient to treat each minute as an independent unit for avoidance analysis. The responses of both species over a 3-y period were generally similar to responses they make to predators as described by Inuit hunters.

Beluga whales responded to oncoming vessels by (1) fleeing at speeds of up 20 km/h from distances of 20 to 80 km, (2) abandoning normal pod structure, and (3) modifying vocal behavior and/or emitting alarm calls. Narwhals, in contrast, generally demonstrated a "freeze" response, lying motionless or swimming slowly away (as far as 37 km down the ice edge), huddling in groups, and ceasing sound production. There was some evidence of habituation and reduced avoidance 2 to 3 d after onset. Due to the detailed and extensive nature of these observations, data from each season, and how they are interpreted here, are given in detail.

The 1982 season observations by LGL & Greeneridge (1986) involved a single passage of an icebreaker with both ice-based and aerial measurements on 28 June 1982. Four groups of narwhals (n = 9 to 10, 7, 7, and 6) responded when the ship was 6.4 km away (exposure RLs of ~100 dB re: 1 µPa in the 150- to 1,150-Hz band). At a later point, observers sighted belugas moving away from the source at > 20 km (exposure RLs of ~90 dB re: 1 µPa in the 150- to 1,150-Hz band). The total number of animals observed fleeing was about 300, suggesting approximately 100 independent groups (of three individuals each), which is the sample size used here. No whales were sighted the following day, but some were sighted on 30 June, with ship noise audible at spectrum levels of approximately 55 dB re 1 µPa/Hz (up to 4 kHz).

Observations during 1983 (LGL & Greeneridge, 1986) involved two ice-breaking ships with aerial survey and ice-based observations during seven sampling periods. As the first vessel approached at a distance of about 65 km, ice-based observers noted reactions from both narwhals (seven groups) and belugas (eight groups) (exposure RLs of ~101 to 105 dB re: 1 µPa in the 20- to 1,000-Hz band). After 22 h without operation, the vessel commenced ice-breaking, and a second icebreaker approached (exposure RLs of ~120 dB re: 1 µPa in the 20- to 1,000-Hz band). This resulted in the rapid movement of > 225 belugas (estimated as a sample size of 75 for this analysis); belugas were neither seen nor heard for the remainder of the second observation period. Behavioral responses were also observed for 10 groups of narwhals. A total of 73 narwhals were seen and/or heard, but their reactions are not clearly reported and are thus excluded from analysis here. At the onset of the third sampling period, following a 4.5-h silent interval, four narwhal groups were observed in nominal social behavior (diving and vocalizing). An ice-breaking vessel operated intermittently, but no change was observed in narwhal behavior. Belugas in the area did modify vocalization parameters during operations (exposure RLs of ~116 dB re: 1 µPa in the 20- to 1,000-Hz band). A 6-h quiet interval was followed by 10.5 h of ice-breaking operation, but bad weather precluded animal observations. After an additional 9-h hiatus, ice-breaking commenced again by both vessels (exposure RLs of ~121 dB re: 1 µPa in the 20- to 1,000-Hz band). Ice-based observers documented 14 narwhals and 11 belugas leaving the area, and aerial surveys indicated 80% of 673 belugas moving away from sound sources (estimated number of groups calculated as [.8]*[673/3] = 179.5). As noise levels from ice-breaking operations diminished, a total of 45 narwhals returned to the area and engaged in diving and foraging behavior. The sixth observation period followed 6.5 h without a vessel in the area, during which 30 belugas (estimated as 10 groups) and 15 narwhals (estimated as five groups) were observed diving in the area (exposure RLs of ~105 dB re: 1 µPa in the 20- to 1,000-Hz band). A single beluga vocal response was noted at RL = 116 dB re: 1 µPa in the 20- to 1,000-Hz band. Aerial surveys indicated dense concentrations of narwhals (*n* = 50) and belugas (*n* = 400) apparently foraging well away from the disturbance site. During the final sampling period, following an 8-h quiet interval, no reactions were seen from 28 narwhals and 17 belugas (exposure RLs ranging up to 115 dB re: 1 µPa).

The final season (1984) reported in LGL & Greeneridge (1986) involved aerial surveys before, during, and after the passage of two ice-breaking ships. The lack of ice camps precluded acoustic measurements as well as behavioral observations. A preliminary survey was conducted the day before operations, and an additional aerial survey was conducted as both ships commenced operating. During operations, no belugas and few narwhals were observed in an area approximately 27 km ahead of the vessels, and all whales sighted over 20 to 80 km from the ships were swimming strongly away. Additional observations confirm the remarkable spatial extent of avoidance reactions to this sound source in this context. In the absence of acoustic measurements, however, it was necessary to estimate RLs from the detailed data from the same ice-breaking vessel during the previous season.

Behavioral responses at fairly low exposure RLs are suggested by studies of some other mid-frequency cetaceans as well. Gordon et al. (1992) conducted opportunistic visual and acoustic monitoring of sperm whales in New Zealand exposed to nearby whale-watching boats (within 450 m). Individuals could not be used as the units of analysis because it was difficult to re-sight specific individuals during both exposure and control conditions. Sperm whales respired significantly less frequently, had shorter surface intervals, and took longer to start clicking at the start of a dive descent when boats were nearby than when they were absent. Noise spectrum levels of whale-watching boats ranged from 109 to 129 dB re: 1 µPa/Hz. Over a bandwidth of 100 to 6,000 Hz, equivalent broadband source levels are ~157 dB re: 1 µPa-m; RLs at a range of 450 m are ~104 dB re: 1 µPa.

Palka & Hammond (2001) applied a General Additive Model to line transect data to estimate the range at which mid-frequency cetaceans typically responded to the noise of research vessels. The subjects were Atlantic white-sided dolphins in the Gulf of Maine and white-beaked dolphins (*Lagenorhynchus albirostris*) in the North Sea. The white-sided dolphins exhibited simple avoidance behavior (as indicated by their orientations) out to an estimated range of 592 m based on 85 group sightings (*n* > 1). White-beaked dolphins actually approached vessels between 150 and 300 m away, but demonstrated avoidance at distances of 300 to 700 m. Typical avoidance distance was estimated as 716 m based on 48 groups sighted.

Buckstaff (2004), using repeated samples of the behavior of 14 individual bottlenose dolphins, observed 1,233 vessel approaches (within 400 m) near Sarasota, Florida. Dolphin whistle rates became elevated before vessel noise was detectable to the researcher listening via towed hydrophones. Vessel RLs measured near dolphin subjects ranged from 113 to 138 dB re: 1 µPa. Dolphin vocal responses were observed before vessel sounds were audible, and apparently occurred with RLs in the 110 to < 120 dB re: 1 µPa category.

Morisaka et al. (2005) compared whistles from three populations of Indo-Pacific bottlenose dolphins (*Tursiops aduncus*). One population was exposed to vessel noise with spectrum levels of ~85 dB re: 1 µPa/Hz in the 1- to 22-kHz band (broadband RL ~128 dB re: 1 µPa) as opposed to ~65 dB re: 1 µPa/Hz in the same band (broadband RL ~108 dB re: 1 µPa) for the other two sites. Dolphin whistles in the noisier environment had lower fundamental frequencies and less frequency modulation, suggesting a shift in sound parameters as a result of increased ambient noise.

Morton & Symonds (2002) used census data on killer whales in British Columbia to evaluate avoidance of nonpulse AHD sources. They considered unusually long time scales, comparing pre-exposure data from 1985 to 1992, exposure from 1993 to 1998, and post-exposure from 1999 to 2000. The response data were simply presence or absence, making it difficult to assess RLs. Using some monitoring and reasonable assumptions, however, they estimated audibility ranges throughout the complex study area. Avoidance ranges were *ca.* 4 km. Also, there was a dramatic reduction in the number of days "resident" killer whales were sighted during AHD-active periods compared to pre- and post-exposure periods and a nearby control site. Morton & Symonds did not indicate how many pods were involved in their analysis. Consequently, we assume a single independent group in our analysis.

Monteiro-Neto et al. (2004) studied avoidance responses of tucuxi (*Sotalia fluviatilis*) to Dukane® Netmark ADDs. Source characteristics are not given, but identical devices were used by Culik et al. (2001), and acoustic parameters are reported in detail there (and in the "Cell 9" section). In a total of 30 exposure trials, ~5 groups each demonstrated significant avoidance compared to 20 pinger off and 55 no-pinger control trials over two quadrats of about 0.5 km^2. Neither avoidance range nor RLs are given, but based upon a central distance from the quadrat of 10 m, and assuming 15 log R transmission loss in this shallow environment (water depth 1 to 5 m), estimated exposure RLs were ~115 dB re: 1 µPa.

The only specific situation involving exposure of wild marine mammals to active mid-frequency military sonar for which exposure conditions are known with any degree of specificity involved incidental exposure of killer whales to sounds from the naval vessel USS *Shoup* (NRL, 2004a, 2004b; NMFS, 2005). A group (J-pod) of southern resident killer whales in the eastern Strait of Juan de Fuca and Haro Strait, Washington, was observed by researchers before, during, and after the approaching USS *Shoup* transmitted sonar signals from its 53C sonar at a source level of *ca.* 235 dB re: 1 µPa-m once every *ca.* 28 s for several hours. At its point of closest approach, the mean direct-path RL within a specified area around the animals was *ca.* 169 dB re: 1 µPa (NRL, 2004a, 2004b). As indicated by NMFS (2005), there is some discrepancy in interpretation of the behavioral responses among researchers who were either on the water or who observed video recordings of behavioral responses. The lead researcher following and observing the animals during the event indicated that individuals in the group demonstrated abnormal avoidance behavior, most dramatically at the point of closest approach. However, the behavior of the whales apparently returned to normal within a short period following cessation of sonar transmissions. A severity score of 6 (mild/moderate avoidance) is subsequently reported in the 160 to 170 dB re: 1 µPa bin for this single observation of the group.

Awbrey & Stewart (1983) played back semi-submersible drillship sounds (source level: 163 dB re: 1 µPa-m) to belugas in Alaska. They reported avoidance reactions at 300 and 1,500 m and approach by groups at a distance of 3,500 m (RLs ~110 to 145 dB re: 1 µPa over these ranges assuming a 15 log R transmission loss). Similarly, Richardson et al. (1990b) played back drilling platform sounds (source level: 163 dB re: 1 µPa-m) to belugas in Alaska. They conducted aerial observations of eight individuals among ~100 spread over an area several hundred meters to several kilometers from the sound source and found no obvious reactions. Moderate changes in movement were noted for three groups swimming within 200 m of the sound projector.

A number of additional studies (Rendell & Gordon, 1999; Chilvers & Corkeron, 2001; Bordino et al., 2002; Williams et al., 2002; Cox et al., 2003; Hastie et al., 2003; Lusseau, 2003; Foote et al., 2004; Scheifele et al., 2005) were reviewed in detail. The results were excluded from Table 17 due to limited or no information on animal numbers and/or location relative to the source, acoustic properties of sources, propagation variables, or received exposure conditions. The general observations of each study are given here briefly. Hastie et al. (2003) documented increased swimming and diving synchrony of bottlenose dolphins off northern Scotland in the presence of vessel traffic. Lusseau (2003) observed effects on behavior of New Zealand bottlenose dolphins within 400 m of boats. Chilvers & Corkeron (2001) considered differences in behavior of bottlenose dolphins that do and do not forage around trawlers. Williams et al. (2002) observed that some killer whales adopt erratic movement patterns, suggestive of avoidance, when whale-watching vessels accelerate to intersect the whale's course. RLs of vessel sound increased approximately 14 dB with increased speed associated with leapfrogging. Bordino et al. (2002) determined that ADDs were initially effective at reducing by-catch of Franciscana dolphins in Argentine subsistence gillnet fisheries. Cox et al. (2003) investigated reactions of bottlenose dolphins to Dukane® NetMark 1000 ADDs attached to commercial gillnets and found very limited to no behavioral avoidance. A group of long-finned pilot whales (*Globicephala melas*) demonstrated significant elevations of whistle rates following each exposure to mid-frequency military sonar reported to be at a "high" level (Rendell & Gordon, 1999).

Finally, two recent papers deal with important issues relating to changes in marine mammal vocal behavior as a function of variable background noise levels. Foote et al. (2004) found increases in the duration of killer whale calls over the period 1977 to 2003, during which time vessel traffic in Puget Sound, and particularly whale-watching boats around the animals, increased dramatically. Scheifele et al. (2005) demonstrated that belugas in the St. Lawrence River increased the levels of their vocalizations as a function of the background noise level (the "Lombard Effect"). (See also Parks et al., 2007, for a related new paper on mysticetes.) These papers demonstrate some degree of plasticity in the vocal signal parameters of marine mammals in response to the ambient condition (likely affected by the presence of human sound sources). These studies were not particularly amenable to the kind of analysis conducted in the severity scaling. We note the particular importance of direct measurements of noise impacts on marine mammal vocalization and communication systems.

Laboratory Observations (Cell 6)
Several researchers conducting laboratory experiments on hearing and the effects of nonpulse sounds on hearing in mid-frequency cetaceans have reported concurrent behavioral responses. Nachtigall et al. (2003) reported that noise exposures up to 179 dB re: 1 μPa and 55-min duration affected the trained behaviors of a bottlenose dolphin participating in a TTS experiment. Finneran & Schlundt (2004) provided a detailed, comprehensive analysis of the behavioral responses of belugas and bottlenose dolphins to 1-s tones (RLs 160 to 202 dB re: 1 μPa) in the context of TTS experiments. Romano et al. (2004) investigated the physiological responses of a bottlenose dolphin and a beluga exposed to these tonal exposures and demonstrated a decrease in blood cortisol levels during a series of exposures between 130 and 201 dB re: 1 μPa. Collectively, the laboratory observations suggested the onset of behavioral response at higher RLs than did field studies (see Table 16). The differences were likely related to the very different conditions and contextual variables between untrained, free-ranging individuals vs laboratory subjects that were rewarded with food for tolerating noise exposure.

High-Frequency Cetaceans/Nonpulses (Cell 9)

Numerous controlled studies have been conducted recently on the behavioral reactions of high-frequency cetaceans to various nonpulse sound sources both in the field (Culik et al., 2001; Johnston, 2002; Olesiuk et al., 2002) and in laboratory settings (Kastelein et al., 1997, 2000, 2005, 2006a). However, only one high-frequency species (harbor porpoise) has been extensively studied. For that species, sufficient data are available to estimate behavioral response magnitude vs received exposure conditions. The original studies were attempts to reduce harbor porpoise by-catch by attaching warning pingers to fishing gear. More recent studies consider whether ADDs and AHDs also exclude harbor porpoises from critical habitat areas and whether these devices affect harbor porpoise behavior in controlled laboratory conditions.

The combined wild and captive animal data (summarized in Table 18) clearly support the observation that harbor porpoises are quite sensitive to a wide range of human sounds at very low exposure RLs (~90 to 120 dB re: 1 μPa), at least for initial exposures. This observation is also evident in the severity scaling analysis for Cell 9 (Table 19). All recorded exposures exceeding 140 dB re: 1 μPa induced profound and sustained avoidance behavior in wild harbor porpoises. Harbor porpoises also tend to avoid boats, although Dall's porpoises do not (Richardson et al., 1995). Whether this apparently high degree of behavioral sensitivity by harbor porpoises to anthropogenic sounds extends to other high-frequency cetacean species (or to nonpulse sources other than ADDs, AHDs, and boats) is unknown. However, given the lack of information to the contrary, such a relationship should be assumed as a precautionary measure.

Habituation to sound exposure was noted in some but not all studies. In certain field conditions, strong initial reactions of high-frequency cetaceans at relatively low RLs appeared to wane rather rapidly with repeated exposure (Cox et al., 2001). In contrast, several laboratory observations showed little or no indication of reduced behavioral sensitivity as a function of exposure experience (Kastelein et al., 1997, 2005).

Field Observations (Cell 9)
Kraus et al. (1997) found (and Barlow & Cameron, 2003, later confirmed) that ADDs can affect by-catch rates of harbor porpoises in commercial fishing applications. Kraus et al. (1997) found that nets with Dukane® pingers (10-kHz fundamental frequency, 300-ms duration, 132 dB re: 1 μPa source level) were sufficiently avoided that significantly fewer porpoises were entangled than in nets lacking pingers. Their observations suggest an ADD avoidance range of at least 10 m (exposure RL ~110 dB re: 1 μPa) but are not explicit enough in documenting exposure conditions or individual responses to include in the behavioral scoring analysis here.

Culik et al. (2001) conducted behavioral observations of groups of harbor porpoises near Vancouver Island before, during, and after the removal of a PICE pinger (eight different wideband swept frequency signals between 20 and 160 kHz; 300-ms duration at random intervals [5 to 30 s]; max. broadband SL = 145 dB re: 1 μPa @ 1 m). Source characteristics of the alarm were known, but propagation measurements were not made *in situ*. Exposure RLs are estimated here based on source characteristics and assumptions regarding propagation, allowing for measures of similar sources in similar conditions. A large exclusion zone of approximately 530-m radius surrounding active acoustic alarms was observed (corresponding to exposure RLs of ~90 to 100 dB re: 1 μPa). Individual sighting and avoidance data during CEE active and control conditions were scored for individuals within and outside this exclusion zone (see Table 18).

Johnston & Woodley (1998) conducted an extensive survey of AHDs used in the Bay of Fundy to exclude pinnipeds from salmon aquaculture sites. Based on the behavioral observations of Olesiuk et al. (1996), Johnston & Woodley (1998) determined that harbor porpoises were likely being excluded from extensive areas of important habitat as a result of overlapping AHD deployments. This study lacked the discrete observational data necessary for analysis here, but two subsequent studies contained such measurements for harbor porpoises exposed to AHDs.

Olesiuk et al. (2002) conducted a controlled exposure in which they deactivated an array of four Airmar® AHDs for 3 wk and then activated the array for three 3-wk intervals over an 18-wk period. Source characteristics are known (10-kHz fundamental frequency; 194 dB re: 1 μPa-m (peak-to-peak) source level; series of 1.8-ms pulses, repeated at 40-ms intervals grouped into 2.3-s trains separated by 2.1-s quiet periods). However, no empirical acoustic measurements were obtained. Exposure RLs were estimated here based on source characteristics and simple assumptions about the propagation of high-frequency sounds in shallow-water environments. Active AHDs resulted in clear avoidance behavior by individuals and groups of harbor porpoises. The sighting rate during active periods as a percent of that during control periods was only 1.4% at ranges from 400 to 599 m, 2.5 to 3.3% at 600 to 2,499 m, and 8.1% at 2.5 to 3.5 km. RLs at 3.5 km were estimated to be ~123 dB re: 1 μPa. Avoidance data during active and control periods were scored here for individuals within the various exposure zones (Table 18).

Johnston (2002) observed similar harbor porpoise behavioral avoidance of active AHDs. They used an Airmar® dB II Plus AHD System (10-kHz fundamental frequency; 180 dB re: 1 μPa-m source level, producing a short train of 2.5-ms signals repeated every 17 s) deployed from a small boat. They sighted fewer animals when the AHD was active, and these animals were significantly further away than during control phases. Approximate exposure RLs at the point of closest approach were estimated here as ~128 dB re: 1 μPa; mean closest approach distance was consistent with exposure RLs of ~125 dB re: 1 μPa.

Additional field observations of harbor porpoises suggest that their apparently high degree of behavioral sensitivity extends to sources other than ADDs and AHDs. Koschinski et al. (2003) observed behavioral responses of harbor porpoises to simulated wind turbine noise (max. energy between 30 and 800 Hz; spectral density source levels of 128 dB re: 1 μPa/Hz at 80 and 160 Hz). They sighted harbor porpoises at greater ranges during playbacks of simulated wind turbine noise and observed that animals more frequently used echolocation signals during industrial activity. These data are not scored here, however, due to limited available information about noise exposure conditions and individual behavioral responses.

Finally, while their study was not considered in the severity scaling here, we note the importance of the Cox et al. (2001) observations regarding harbor porpoise habituation. They found that wild porpoises were initially displaced by approximately 208 m from active ADDs, but this displacement decreased by 50% in 4 d, and reached control levels in 10 to 11 d. Because of the potential for habituation, it should be noted that many or most of the field observations reported here, other than those that involve long-duration deployments, are likely most relevant for naïve individuals.

Laboratory Observations (Cell 9)

Relatively extensive laboratory data are available on captive, individual high-frequency cetaceans exposed to some of the same acoustic alarms (ADDs and AHDs) and scaring devices deployed in field applications. We applied our behavioral scoring paradigm to data from each of the captive studies conducted by Kastelein and colleagues, which included relatively detailed information on individual responses and directly measured exposure RLs.

Kastelein et al. (1997) recorded behavioral responses (location, swimming speed, and respiration patterns) of a naïve, captive harbor porpoise exposed to a variety of clicks, tones, and frequency sweeps. All of the relatively low exposure RLs (~90 to 115 dB re: 1 μPa) resulted in strong behavioral avoidance (subjects basically swam rapidly as far from the devices as possible within the enclosure) as well as changes in swimming speed and breathing patterns. Although this response quickly abated following noise cessation, no habituation was observed across multiple exposure events. Data from individual exposure trials were presented by Kastelein et al. and are analyzed here. To avoid pseudoreplication, these data are inversely weighted by the total number of trials to approximate a single exposure for the individual. Based on harbor porpoise hearing measurements (Andersen, 1970) and the Kastelein et al. (1997) data on behavioral reactions, Taylor et al. (1997) estimated zones of noise influence (audibility, behavioral disturbance, and hearing damage) for free-ranging harbor porpoises.

Subsequently, Kastelein et al. (2000) exposed two naïve subjects to three different nonpulse sources and observed generally similar behavioral avoidance in all conditions. Pooled data for each subject were scored and reported here; pooled data for each alarm in the dose-response analysis were weighted to equate with a single exposure event for each individual. Kastelein et al. (2001) later measured similar behavioral responses of the same two individual harbor porpoises to three different acoustic alarms, but these data were not included in this analysis because subjects were no longer naïve to controlled noise exposures.

Kastelein et al. (2005) exposed two additional naïve harbor porpoises to various sounds associated with underwater data transmission systems (clicks, tones, sweeps, and impulsive distance sensors with a range of source characteristics). They directly measured source levels of each sound type and RLs at numerous positions within the experimental pool. Observed behavioral responses (avoidance and changes in swimming and respiration patterns) were very similar to those during the previous Kastelein et al. (1997, 2000, 2001) studies. Pooled data for each individual response and source type were analyzed here in the same manner as we applied to the Kastelein et al. (2000) measurements. Kastelein et al. (2006a) exposed yet another naïve individual harbor porpoise and reported very similar findings, which we incorporated as a single pooled result, with all exposures equally weighted.

Pinnipeds in Water/Nonpulses (Cell 12)

The effects of nonpulse exposures on pinnipeds in water are poorly understood. Studies for which enough information was available for our analysis include field exposures of harbor seals to AHDs (Jacobs & Terhune, 2002) and of translocated diving northern elephant seals to a research tomography source (Costa et al., 2003), as well as responses of captive harbor seals to underwater data communication sources (Kastelein et al., 2006b). These limited data (see Table 20) suggest that exposures between ~90 and 140 dB re: 1 µPa generally do not appear to induce strong behavioral responses in pinnipeds exposed to nonpulse sounds in water; no data exist regarding exposures at higher levels. The severity scaling for Cell 12 is given in Table 21.

It is important to note that among these studies of pinnipeds responding to nonpulse exposures in water, there are some apparent differences in responses between field and laboratory conditions. In contrast to the mid-frequency odontocetes, captive pinnipeds responded more strongly at lower levels than did animals in the field. Again, contextual issues are the likely cause of this difference. Captive subjects in the Kastelein et al. (2006b) study were not reinforced with food for remaining in noise fields, whereas free-ranging subjects may have been more tolerant of exposures because of motivation to return to a safe location (Costa et al., 2003) or to approach enclosures holding prey items (Jacobs & Terhune, 2002).

Field Observations (Cell 12)

Jacobs & Terhune (2002) observed harbor seal reactions to Airmar® dB plus II AHDs (general source characteristics given in the "Cell 9" section above; source level in this study was 172 dB re: 1 µPa-m) deployed around aquaculture sites. From 1 to 10 AHDs were deployed around nine different sites. Jacobs & Terhune measured received SPLs around the AHDs and measured the behavior of seals in the surrounding area. Seals in this study were generally unresponsive to sounds from the AHDs. During two specific events, individuals came within 43 and 44 m of active AHDs and failed to demonstrate any measurable behavioral response; estimated exposure RLs based on the measures given were ~120 to 130 dB re: 1 µPa. These individual observations are weighted to represent a single observation for this study, scored (as 0), and reported in Table 21.

Costa et al. (2003) measured received noise levels from an ATOC sound source off northern California using acoustic data loggers placed on translocated elephant seals. Subjects were captured on land, transported to sea, instrumented with archival acoustic tags, and released such that their transit would lead them near an active ATOC source (at 939-m depth; 75-Hz signal with 37.5-Hz bandwidth; 195 dB re: 1 µPa-m max. source level, ramped up from 165 dB re: 1 µPa-m over 20 min) on their return to a haulout site. Costa et al. provided a wide range of detailed quantitative measures of individual diving behavior, responses, and exposure RLs in well-characterized contexts; this kind of information was ideal for the present purposes. Dive depth and duration, descent/ascent velocity, surface interval, and exposure RL were recorded from a total of 14 seals. An additional three seals were exposed to the ATOC source during translocations and behavioral observations were made, but exposure RLs were unavailable. Seven control seals were instrumented similarly and released when the ATOC source was not active. Received exposure levels of the ATOC source for experimental subjects averaged 128 dB re: 1 µPa (range 118 to 137) in the 60- to 90-Hz band. None of the instrumented animals terminated dives or radically altered behavior upon exposure, but some statistically significant changes in diving parameters were documented in nine individuals. The behavioral scores assigned here for statistically significant responses were either three or four depending on the change in diving behavior during exposure relative to mean values for the same individuals before and after exposure (< 50% change scored 3; > 50% change scored 4). Translocated northern elephant seals exposed to this particular nonpulse source (ATOC) began to demonstrate subtle behavioral changes at ~120 to 140 dB re: 1 μPa exposure RLs (Table 21).

Several other field studies (discussed briefly below) were considered but not included in the behavioral analyses due to limited information about source and/or propagation characteristics, individual responses during and/or in the absence of exposure, or both. While studying cetaceans, Richardson et al. (1990b, 1991) made some observation of ringed and bearded seal responses to playbacks of underwater drilling sounds. Their findings generally suggested a fairly high degree of tolerance by exposed pinnipeds to these sounds. This contrasts to some extent with the results of Frost & Lowry (1988) who found some reduction in ringed seal densities around islands on which drilling was occurring. Norberg & Bain (1994) made detailed acoustic measurements of several arrays of Cascade Applied Sciences® AHDs (11.9- to 14.7-kHz frequency sweeps; 195 dB re: 1 μPa-m source level; 1-ms pulse produced in 57 to 58 discrete pulse chirps of 2.3-s total duration). These devices were placed on the Chittenden Locks in Puget Sound, Washington, in an effort to dissuade predation of wild steelhead trout by California sea lions. Behavioral responses of individual animals, however, were not reported. Norberg (2000) evaluated the behavioral responses of California sea lions to Airmar® AHDs (10-kHz fundamental frequency; 195 dB re: 1 μPa-m source level; short train of 2.5-ms signals repeated every 17 s) intended to reduce predation on salmonids in aquaculture facilities. Behavioral observations suggested limited behavioral deterrence by the devices (predation rates were similar in experimental and control conditions), but measures of RLs and individual response behavior are absent. Yurk (2000) also observed pinnipeds exposed to AHDs in the context of fisheries interactions. He determined that active AHDs were more effective than a mechanical barrier or altered lighting conditions in dissuading harbor seals from preying on fish under bridges. Again, however, insufficient information regarding received sounds and individual responses is available to consider these observations explicitly here. Koschinski et al. (2003) observed harbor seals during underwater playbacks of simulated wind turbine noise (maximum energy between 30 and 800 Hz; spectral density source levels of 128 dB re: 1 μPa/Hz at 80 and 160 Hz). Harbor seals were sighted at greater distances during playbacks than during control conditions. However, limited information on received exposures and individual behavioral responses precluded inclusion in our analysis. Moulton et al. (2003, 2005) studied ringed seals before and during the construction and operation of an oil production facility. They found little or no avoidance of the area around the various industrial sources, most of which emitted nonpulses. Because of the continuous exposure to multiple sound sources at varying distances, this study did not produce data on discrete exposures and responses.

Laboratory Observations (Cell 12)

Kastelein et al. (2006b) exposed nine captive harbor seals in a ~25 × 30 m enclosure to nonpulse sounds used in underwater data communication systems (similar to acoustic modems). Test signals were identical to those used by Kastelein et al. (2005) in harbor porpoise exposure studies (frequency modulated tones, sweeps, and bands of noise with fundamental frequencies between 8 and 16 kHz; 128 to 130 [± 3] dB re: 1 μPa-m source levels; 1- to 2-s duration [60-80% duty cycle]; or 100% duty cycle). They recorded seal positions and the mean number of individual surfacing behaviors during control periods (no exposure), before exposure, and in 15-min experimental sessions (*n* = 7 exposures for each sound type). Background noise and exposure RLs (in terms of L_{eq}; 32-s total time) were measured at numerous positions around the enclosure for each acoustic source. Acoustic discomfort was recognized based on movement out of areas that animals used during control periods. An acoustic discomfort threshold was calculated for the group of seals for each source type, and for each sound source this was *ca.* 107 dB re: 1 μPa. Seals generally swam away from each source, avoiding it by ~5 m, although they did not haul out of the water or change surfacing behavior. Seal reactions did not appear to wane over repeated exposure (i.e., there was no obvious habituation), and the colony of seals generally returned to baseline conditions following exposure.

For the behavioral analysis conducted here, the Kastelein et al. (2006b) results were interpreted as follows. Because the behavior of individuals within the same pool at the same time cannot be considered independent, the group of nine harbor seals was considered a single observation. Because of similarity of sources and exposure conditions and the close temporal timing of exposures, we combined observations across the four sound types and include a single observation within each appropriate 10-dB bin. Exposures between ~80 and 107 dB re: 1 μPa seemed insufficient to induce behavioral avoidance in the colony of seals, but higher exposures were considered sufficient. Consequently, single observations indicating no response (0) appear in the 80 to 90 and in the 90 to 100 dB re: 1 μPa exposure bins, and a single observation indicating avoidance behavior (6) is shown in the 100 to 110 dB re: 1 μPa condition (Table 21).

Pinnipeds in Air/Nonpulses (Cell 15)

There has been considerable effort to study the effects of aerial nonpulse sounds on pinniped behavior, primarily involving rocket launches, aircraft overflights, power-boat approaches, and construction noise. Unfortunately, many of the studies are difficult to interpret in terms of exposure RL and individual or group behavioral responses. In many cases, it was difficult or impossible to discern whether the reported behavioral response was induced by the noise from a specific operation or some correlated variable such as its visual presence. For these reasons, most of the observational studies of behavioral disturbance are not appropriate for quantitative analyses relating exposure level and scored behavioral response. However, a number of the technical reports and analyses of rocket launches are relevant for this cell and contain sufficiently detailed information regarding estimated RLs. These observations are complicated, however, by the fact that all studies were conducted in the same general area with subjects likely habituated to the presence of launch noise. Further, in many cases, exposures contained both a nonpulse component and a pulse component (described below). Only those observations for which there was clearly just nonpulse exposure were considered in the severity scaling analysis (Thorson et al., 1999, 2000b; Berg et al., 2002).

The limitations of these and other potentially applicable studies resulted in a very limited data set for use in this analysis (see summary in Table 22 and severity scaling analysis in Table 23). As a general statement from the available information, pinnipeds exposed to intense (~110 to 120 dB re: 20 µPa) nonpulse sounds often leave haulout areas and seek refuge temporarily (minutes to a few hours) in the water. In contrast, pinnipeds exposed to distant launches at RLs ~60 to 70 dB re: 20 µPa tend to ignore the noise. It is difficult to assess the relevance of either of these observations to naïve individuals, however, given the repeated exposure of colonies studied to such noise events. Also, there are strong species differences, with harbor seals being much more responsive than northern elephant seals (e.g., Holst et al., 2005a, 2005b). Due to the limitations of the available data, it is not currently possible to make any further general characterizations regarding this condition.

A series of highly detailed, quantitative analyses on the behavior of pinnipeds exposed to the sounds of various large missile launches were reviewed. These sources generally produce sustained, generally low-frequency (little energy above 1,000 Hz) "rumbling" sounds lasting tens of seconds (nonpulse) associated with launch boosters, as well as a sonic boom (pulse) in flight as the rocket goes supersonic. Extensive research has been conducted on the effects of both sound types on pinnipeds. Nonpulse exposures are considered in this section, whereas behavioral responses to the pulse component of some of the same launches are considered in Appendix B. Because many measurements were made on the same few colonies of pinnipeds that were exposed to multiple launches, it is likely that some of the same individuals were resampled. Therefore, we weighted the combined results across studies for each species and breeding location into a single observation for the behavioral analysis here. That is, we considered each species in an individual breeding colony a single unit of observation across studies. The results were pooled accordingly in Table 22, but the studies are discussed longitudinally below. The studies discussed below reported exposure conditions on or near pinniped breeding rookeries during launches of different types of rockets using a variety of metrics, including A-weighted values and a frequency-weighting function derived from the harbor seal audiogram; we used unweighted SPL values for the analysis here.

Thorson et al. (1998) measured harbor seal responses and conducted AEP measurements on seals exposed to a Titan IV A-18 launch from Vandenberg Air Force Base (VAFB), California. They studied colonies both on the mainland at VAFB and on nearby Santa Cruz Island. Unfortunately, the launch occurred at night and during a period of relatively high tide, limiting both the number of seals present on the rookeries and the observation of individuals. However, behavioral monitoring over several days after the launch did not indicate any abandonment of the breeding rookeries at either site. Hearing measures (AEP) on individuals tested before and several hours after the launch did not indicate any loss of sensitivity.

Thorson et al. (1999) conducted similar observations of harbor seals at VAFB and also observed northern elephant seals, California sea lions, and northern fur seals at nearby San Miguel Island. Following the launch (of an Athena 2 IKONOS-1 missile), 33 harbor seals (including six pups) at the VAFB rookery entered the water. They began to return to the beach beginning 16 min after the launch, and no pups were observed to have died as a result of the event. This behavior was considered to represent both minor avoidance and a brief/minor potential or actual separation of females and dependent offspring (scored 6 here). The maximum unweighted SPL value was 119 dB re: 20 µPa. Individuals of the three pinniped species monitored on San Miguel Island reacted similarly. However, their responses were to the sonic boom generated by the rocket once airborne rather than to the nonpulse sounds associated with the launch per se, and thus are not scored here.

Thorson et al. (2000a) conducted observations of harbor seal abundance, distribution, and haulout patterns at VAFB for several days before and after the launch of a Titan II G-13 missile from VAFB. This launch occurred during the middle of the night, precluding direct observation of seal reactions (and behavioral scoring here), although observations on subsequent days indicated generally nominal harbor seal presence and distribution in the area.

Thorson et al. (2000b) measured behavioral and auditory responses of harbor seals at VAFB and behavioral responses of northern elephant seals and California sea lions on San Miguel Island to the launch of a Titan IV B-28 missile from VAFB. They observed all 54 harbor seals at the VAFB site moving from the breeding rookery into the water within 2 min of the onset of the launch (47 entered the water immediately). The maximum unweighted SPL value near the rookery was 116 dB re: 20 µPa; this exposure was considered here to be consistent with a behavioral score of 6 for this group of seals. The sound persisted for several minutes, and the unweighted SEL value was 127 dB re: $(20\ \mu Pa)^2$-s. There was no difference in the hearing capabilities of three young seals tested using AEP methods before and after the missile launch. Neither the California sea lions nor elephant seals on San Miguel Island were observed to respond at all to the "faint" noise associated with the launch, corresponding to a severity scaling score of 0 (Table 23). These sounds were from the launch boosters (nonpulses) rather than sonic booms and were estimated here as ~60 to 70 dB re: 20 µPa based on the measurements and descriptions given.

Berg et al. (2001) obtained similar measurements of behavioral responses of harbor seals at VAFB and California sea lions and northern elephant seals at San Miguel Island to a Delta II EO-1 missile launch from VAFB. Observations were also made of southern sea otter (*Enhydra lutris nereis*) and California brown pelican (*Pelecanus occidentalis californicus*) responses. No harbor seals were hauled out on the VAFB rookery during this launch. Berg et al. note that subsequent harbor seal abundance and distribution in the days after the launch were within normal variability, and there appeared to be no lasting behavioral reactions. Elephant seals and California sea lions at San Miguel Island did not noticeably respond to sounds associated with the launch, which in this case were predominantly the sonic boom (pulse) component.

Berg et al. (2002) measured behavioral responses of harbor seals on VAFB rookeries to the launch of a Titan IV B-34 missile from a launch pad at VAFB ~8.6 km away. At the time of the launch, 38 seals were present at two haulout sites, all of which entered the water immediately following the onset of launch noise. More seals (*n* = 56) were present at the locations 90 min after the launch event, indicating the temporary and minor nature of the disturbance, and no injured animals were located. The avoidance behavior was coincident with a maximum unweighted SPL value near the rookeries of 119 dB re: 20 µPa (unweighted aerial SEL value was 130 dB re: $[20\ \mu Pa]^2$-s).

Finally, Berg et al. (2004) observed behavioral responses of California sea lions, northern elephant seals, and northern fur seals on San Miguel Island to the launch of an Atlas IIAS MLV-14 missile from VAFB. Received signals were sonic booms which had little to no effect on the behavior of the pinnipeds, other than minor orienting behaviors and movements in some of the California sea lions. These results are not scored here, in part because the sounds included pulses.

Other researchers have investigated the effects of other kinds of human activities (e.g., aircraft, motorboats, general human presence) as well as rocket launches on the haulout behavior, including avoidance, of pinnipeds (Allen et al., 1984; Suryan & Harvey, 1998; Born et al., 1999; Moulton et al., 2002). The combined results indicated that hauled-out pinnipeds in certain conditions can be disturbed, significantly in some cases, by the presence of various human activities. However, these studies lack either specific estimates of received noise exposure conditions or individual-specific behavioral responses or both. Additionally, multiple stimuli were generally simultaneously present, including the visual presence of sources, which preclude their inclusion here. Gentry et al. (1990) determined that northern fur seals were generally tolerant of underground explosions and other quarrying operations in relatively close proximity; only a few orienting behaviors were observed in response to the largest blasts. Some acoustic measurements were made, but individual behaviors or group responses and received exposure levels were not reported and were thus not scored here.

Holst et al. (2005a, 2005b) observed behavioral responses in three species of pinnipeds—harbor seal, California sea lion, and northern elephant seal—on San Nicolas Island to 47 small- and mid-sized missile launches over a 4-y period. They observed animal presence and distribution before launches and behavior during and following launches. Some of the missiles generated sonic booms, but the majority of the exposures were relatively low-frequency, long-duration rumbling sounds that would be categorized as nonpulses. During many launches, acoustic measurements were made near the animals whose behavior was videotaped. Peak, SPL, and SEL exposures were reported. This dataset has not been incorporated into the present analysis. However, results indicated that California sea lions had mixed reactions to rocket launches, with some individuals exhibiting startle responses and increased vigilance and others showing virtually no reaction. Northern elephant seal reactions were minimal, consisting only of minor movements and orienting responses that rapidly subsided. Conversely, harbor seals were by far the most responsive of the pinnipeds observed, with many individuals entering the water from haulout sites following rocket launches and failing to return for periods of hours. No cases of long-term pup separation or of injury were documented. If those phenomena had occurred, they would be considered relatively severe in terms of the behavioral scoring paradigm given here and should also be considered as they relate to injury criteria. In California sea lions and northern elephant seals, there were significant correlations between behavioral responses and both the missile's closest distance and the RL of the launch sound near the pinnipeds (SEL). Corresponding relationships for harbor seals were weaker. Holst et al. (2005b) concluded that the temporary behavioral responses, even the relatively severe ones observed in harbor seals, do not appear to have substantial adverse effects on pinniped populations. This conclusion is based on the decades-long occurrence of missile launches and the presence of increasing numbers of pinnipeds of all three species in the area.

(Left to Right): David Kastak, Roger Gentry, Peter Tyack, Brandon Southall, Darlene Ketten, W. John Richardson, Jeanette Thomas, James Miller, Ann Bowles, James Finneran, Charles Greene, Jr., Paul Nachtigall, and William Ellison

This manuscript is respectfully dedicated to our co-author, David Kastak.

Dave was a brilliant scientist, but even more importantly, he was a man with great sincerity, integrity, and a sharp wit. He was an inspiration and mentor to many, and his significant, incisive research on marine mammal cognition and sensory systems over the past two decades provided advances that shaped and will continue to guide the future of these fields. Dave was a valued colleague and treasured friend to all of us. He will be missed but never forgotten.


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