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Criteria and Thresholds for U.S. Navy Acoustic and Explosive Effects Analysis (Phase 4)

Revision 2025.1

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CHANGE LIST

Revision 2025.1

The following lists the updates to this report since the version published in September 2024.

Section 3 MARINE MAMMAL BEHAVIORAL RESPONSE CRITERIA

- Existing behavioral response modeling data in Tables 21-24 and Table E1 were corrected.
- Text in sections 3.1.5, 3.1.6, and 3.1.8 was edited for clarification.

Section 4 SEA TURTLE AUDITORY AND BEHAVIORAL CRITERIA

- Figure 49 includes a new part (b) showing the weighting function.
- The weighting function is defined in a new equation (Eq. 11). Subsequent equation numbers in Section 5 have been updated.
- Table 30 values have been corrected for a rounding error such that all parameters are rounded to 4 significant figures instead of one decimal place.
- Figure 50 has been replaced to correct the Phase 4 composite audiogram from part (a). The corresponding Figure 11 in the executive summary has also been replaced.
- Text has been added to Section 4.1.1.2 to define the weighting function.
- Text has been added to the end of Section 4.1.2.1 to include the values necessary to recreate the exposure functions.

Minor changes have also been made to correct typographical and grammatical errors, and to update or correct cited references throughout the document.

EXECUTIVE SUMMARY

The US Navy conducts acoustic effects analyses to estimate the potential effects of military readiness 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, received exposure levels are compared to acoustic impact criteria and thresholds to estimate the specific effects that animals exposed to Navy-generated sound may experience.

This report presents the criteria and thresholds applied in analyses of acoustic and explosive impacts on marine mammals and sea turtles for fourth phase of the US Navy's programmatic approach to environmental compliance at sea for ranges and operating areas. Previous development of criteria and thresholds occurred as part of Phase 2 (c. 2012) and Phase 3 (c. 2017). To remain consistent with prior terminology, the present criteria and thresholds are referred to as the "Phase 4" criteria and thresholds.

ES-1. MARINE MAMMAL AUDITORY WEIGHTING FUNCTIONS AND EXPOSURE FUNCTIONS

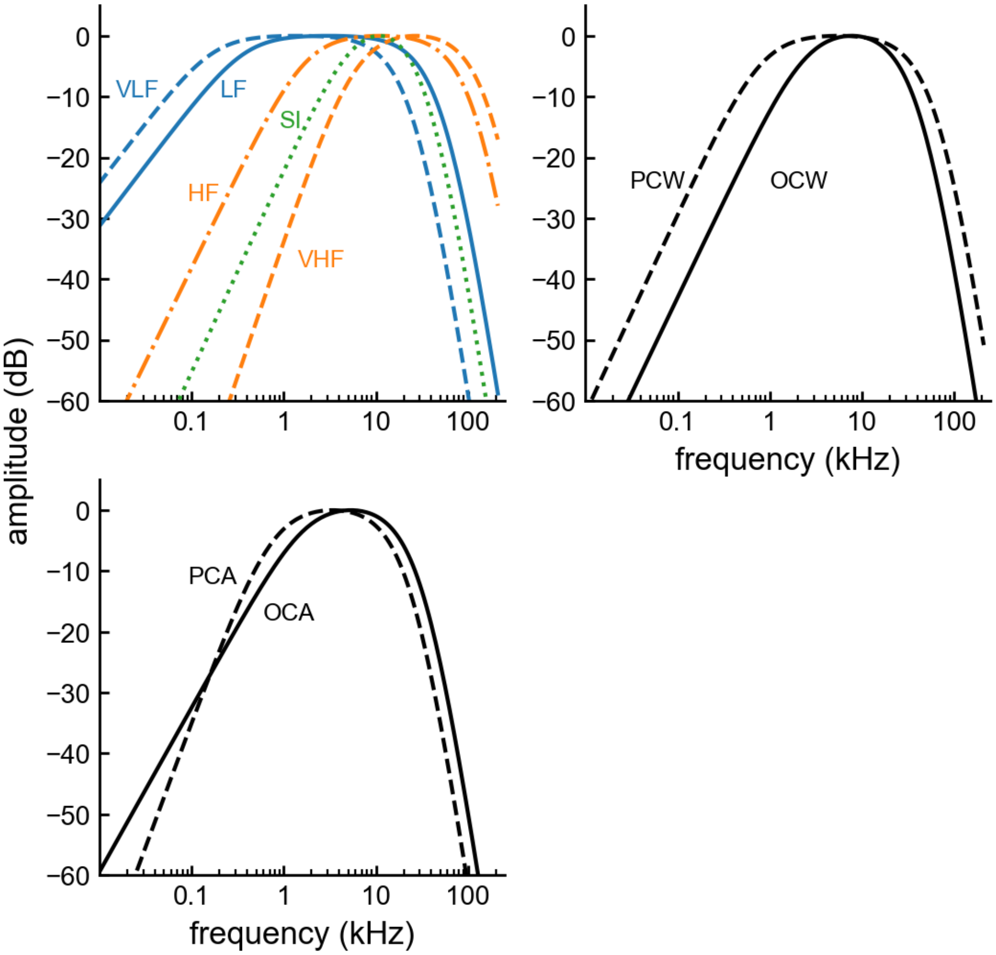
This section describes the rationale and steps used to define criteria and numeric thresholds for predicting auditory effects on marine mammals exposed to non-impulsive acoustic sources (e.g., sonars and other active acoustic sources) and impulsive sources (e.g., explosives, pile driving, and air guns). Since the derivation of Phase 3 acoustic criteria and thresholds, new data have been obtained related to the effects of noise on marine mammal hearing. Therefore, for Phase 4 new criteria and thresholds for the onset of temporary hearing loss and the onset of auditory injury were developed utilizing all relevant, available data.

Marine mammals were divided into nine groups for analysis: very-low frequency cetaceans (group VLF: right, bowhead, fin, blue whales), low-frequency cetaceans (group LF: minke, sei, Bryde's, Omura's, humpback, gray, pygmy right whales), high-frequency cetaceans (group HF: delphinids, monodonts, beaked whales, sperm whales), very high-frequency cetaceans (group VHF: phocoenids, river dolphins, pygmy/dwarf sperm whales), sirenians (group SI: manatees and dugongs), phocid carnivores in water and in air (groups PCW and PCA, respectively: true seals), and otariids and other non-phocid marine carnivores in water and air (groups OCW and OCA, respectively: sea lions, fur seals, walruses, sea otters, polar bears).

For each group, a frequency-dependent weighting function and numeric thresholds for the onset of temporary threshold shift (TTS) and the onset of auditory injury (AINJ) were estimated. The onset of TTS is defined as a TTS of 6 dB measured approximately 2–5 min after exposure. A TTS of 40 dB is used as a proxy for the onset of AINJ; i.e., it is assumed that exposures beyond those capable of causing 40 dB of TTS have the potential to result in permanent threshold shift (PTS) or other auditory injury (e.g., loss of cochlear neuron synapses, even in the absence of PTS). Exposures just sufficient to cause TTS or AINJ are denoted as "TTS onset" or "AINJ onset" exposures. Onset levels are treated as step functions or "all-or-nothing" thresholds: exposures above the TTS or AINJ onset level are assumed to always result in TTS or AINJ, while exposures below the TTS or AINJ onset level are assumed to not cause TTS or AINJ. For non-impulsive exposures, onset levels are specified in frequency-weighted sound exposure level (SEL); for impulsive exposures, dual metrics of weighted SEL and unweighted peak sound pressure level (SPL) are used.

Weighting function amplitudes (Figure 1) are specified using Eq. (1). Table 1 and Table 2 summarize the parameters necessary to calculate the weighting function amplitudes and the weighted threshold values, respectively.

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



- Parameters required to generate the functions are provided in Table 1.

Figure 1. Navy Phase 4 weighting functions for all species groups.

Table 1. Summary of function parameters for use in Eqs. (1) and (2) to generate Phase 4 weighting functions and exposure functions, respectively.

Group	a	b	f_1 (kHz)	f_2 (kHz)	C (dB)	Non-impulse K_{TTS} (dB)	Non-impulse K_{INJ} (dB)	Impulse K_{TTS} (dB)	Impulse K_{INJ} (dB)
VLF	0.990	5.00	0.168	26.6	0.120	177	197	168	183
LF	0.995	5.00	0.376	56.2	0.130	177	197	168	183
HF	1.55	5.00	1.73	129	0.320	181	201	177	192
VHF	2.23	5.00	5.93	186	0.910	160	180	143	158
OCW	1.58	5.00	2.53	43.8	1.37	178	198	168	183
PCW	1.63	5.00	0.810	68.3	0.290	175	195	168	183
SI	1.66	5.00	5.91	37.6	3.61	176	196	167	182
OCA	1.35	5.00	1.75	32.5	1.18	156	176	147	162
PCA	2.05	5.00	0.739	24.4	0.830	133	153	124	139

Table 2. Summary of Phase 4 TTS/AINJ thresholds.

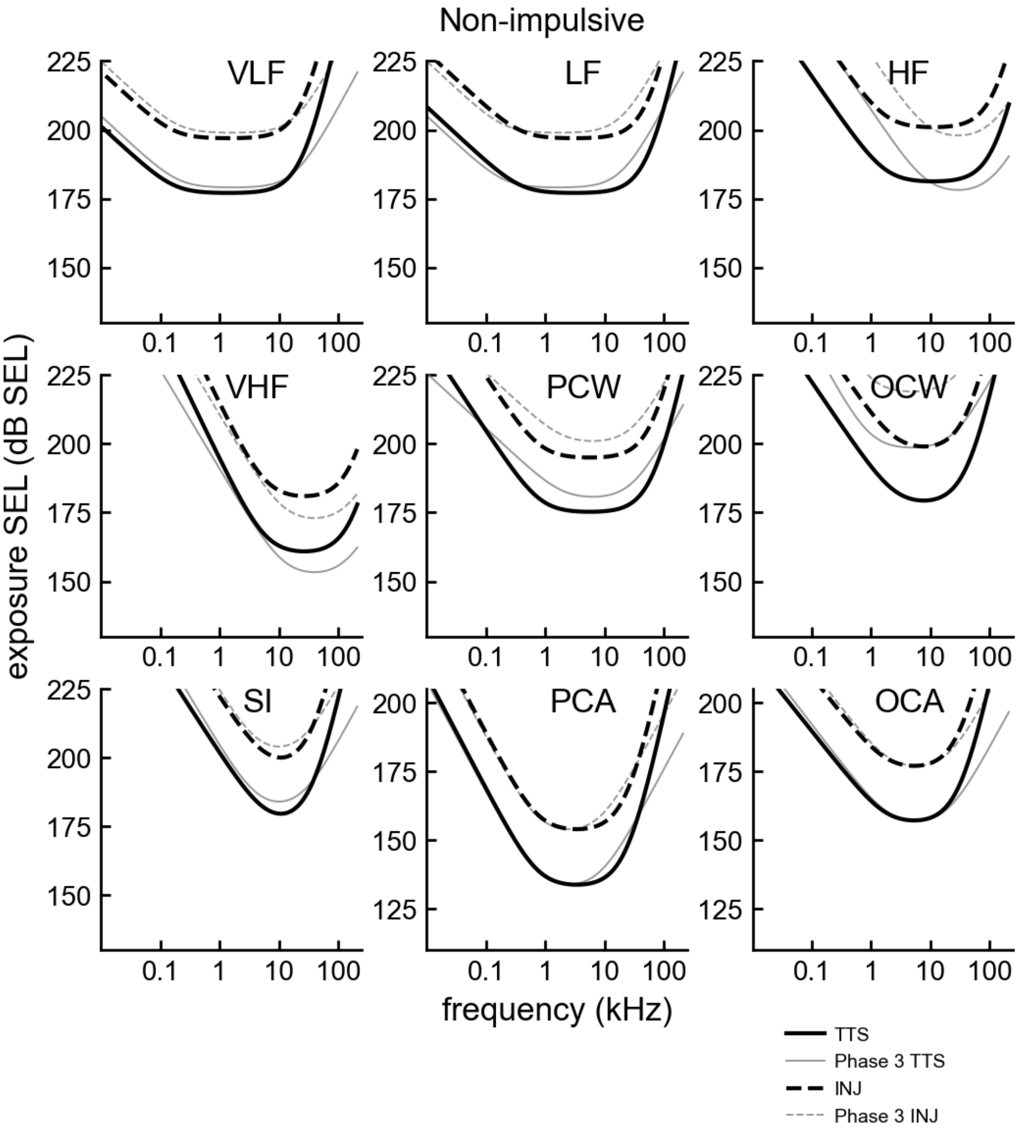
Group	Non-impulsive TTS threshold SEL (weighted)	Non-impulsive INJ threshold SEL (weighted)	Impulsive TTS threshold SEL (weighted)	Impulsive TTS threshold peak SPL (unweighted)	Impulsive INJ threshold SEL (weighted)	Impulsive INJ threshold peak SPL (unweighted)
VLF	177	197	168	216	183	222
LF	177	197	168	216	183	222
HF	181	201	178	224	193	230
VHF	161	181	144	196	159	202
OCW	179	199	170	224	185	230
PCW	175	195	168	217	183	223
SI	180	200	171	219	186	225
OCA	157	177	148	171	163	177
PCA	134	154	125	156	140	162

- SEL thresholds are in dB re 1 $\mu\text{Pa}^2\text{s}$ underwater and dB re 20 $\mu\text{Pa}^2\text{s}$ in air (groups OCA and PCA only).
- Peak SPL thresholds are in dB re 1 μPa underwater and dB re 20 μPa in air (groups OCA and PCA only).

To compare Phase 4 weighting functions and TTS/AINJ SEL thresholds to those used in Phase 3, both the weighting function shape and the weighted threshold values must be considered; the weighted thresholds by themselves only indicate the TTS/AINJ threshold at the most susceptible frequency (based on the relevant weighting function). In contrast, the TTS/AINJ exposure functions incorporate the shape of the weighting function and the weighted threshold value and provide the best means of comparing the frequency-dependent TTS/AINJ thresholds for Phase 3 and 4. Exposure functions are defined using Eq. (2).

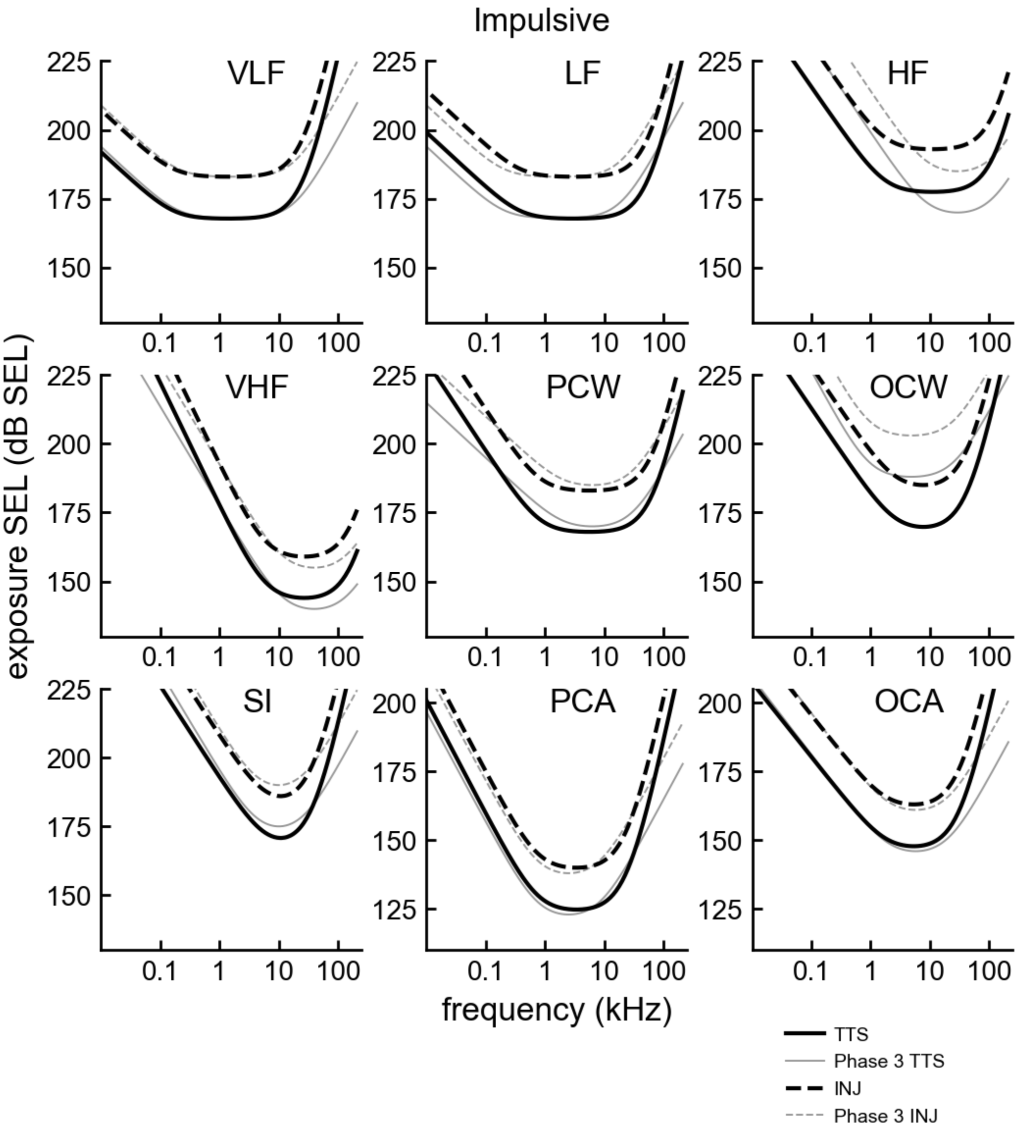
$$E(f) = K - 10\log_{10}\left\{\frac{(f/f_1)^{2a}}{[1+(f/f_1)^2]^a[1+(f/f_2)^2]^b}\right\} \tag{2}$$

Figure 2 and Figure 3 compare the TTS/AINJ exposure functions for non-impulsive sounds (e.g., sonars) and impulsive sounds (e.g., explosions), respectively, used in Phase 3 and Phase 4. Figure 4 and Figure 5 compare exposure functions across species groups for non-impulsive and impulsive exposures, respectively. Table 3 compares the Phase 3 and 4 (unweighted) peak SPL thresholds for impulsive sounds.



- Heavy solid lines: Navy Phase 4 TTS exposure functions (Table 1).
- Thin solid lines: Navy Phase 3 TTS exposure functions.
- Heavy dashed lines: Navy Phase 4 AINJ exposure functions (Table 1).
- Thin dashed lines: Navy Phase 3 AINJ exposure functions.

Figure 2. TTS and AINJ exposure functions for sonars and other (non-impulsive) active acoustic sources.



- Heavy solid lines: Navy Phase 4 TTS exposure functions (Table 1).
- Thin solid lines: Navy Phase 3 TTS exposure functions.
- Heavy dashed lines: Navy Phase 4 AINJ exposure functions (Table 1).
- Thin dashed lines: Navy Phase 3 AINJ exposure functions.

Figure 3. TTS and AINJ exposure functions for explosives, impact pile driving, air guns, and other impulsive sources.

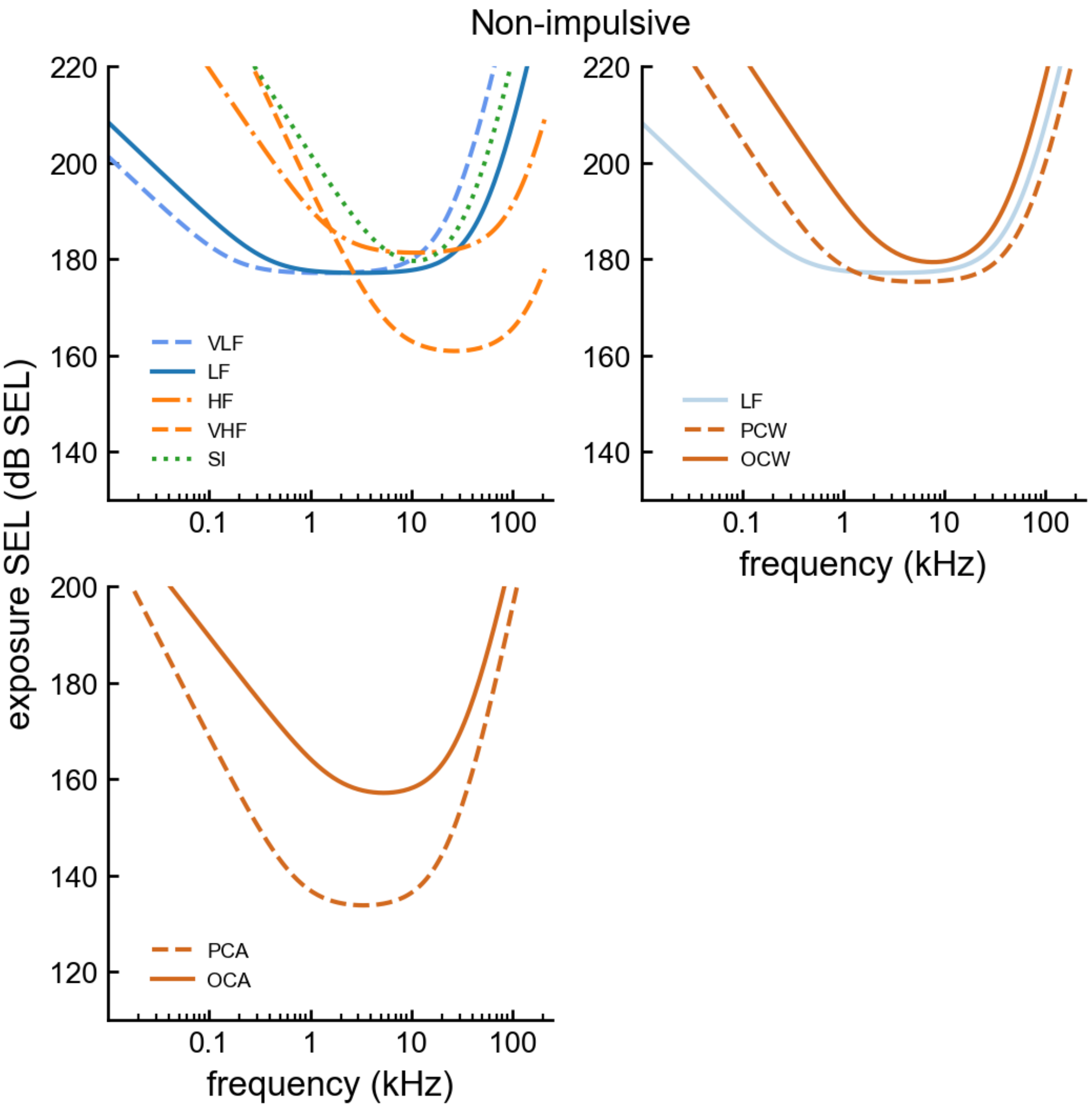


Figure 4. Comparison of Navy Phase 4 TTS exposure functions for sonars and other (non-impulsive) active acoustic sources across species groups.

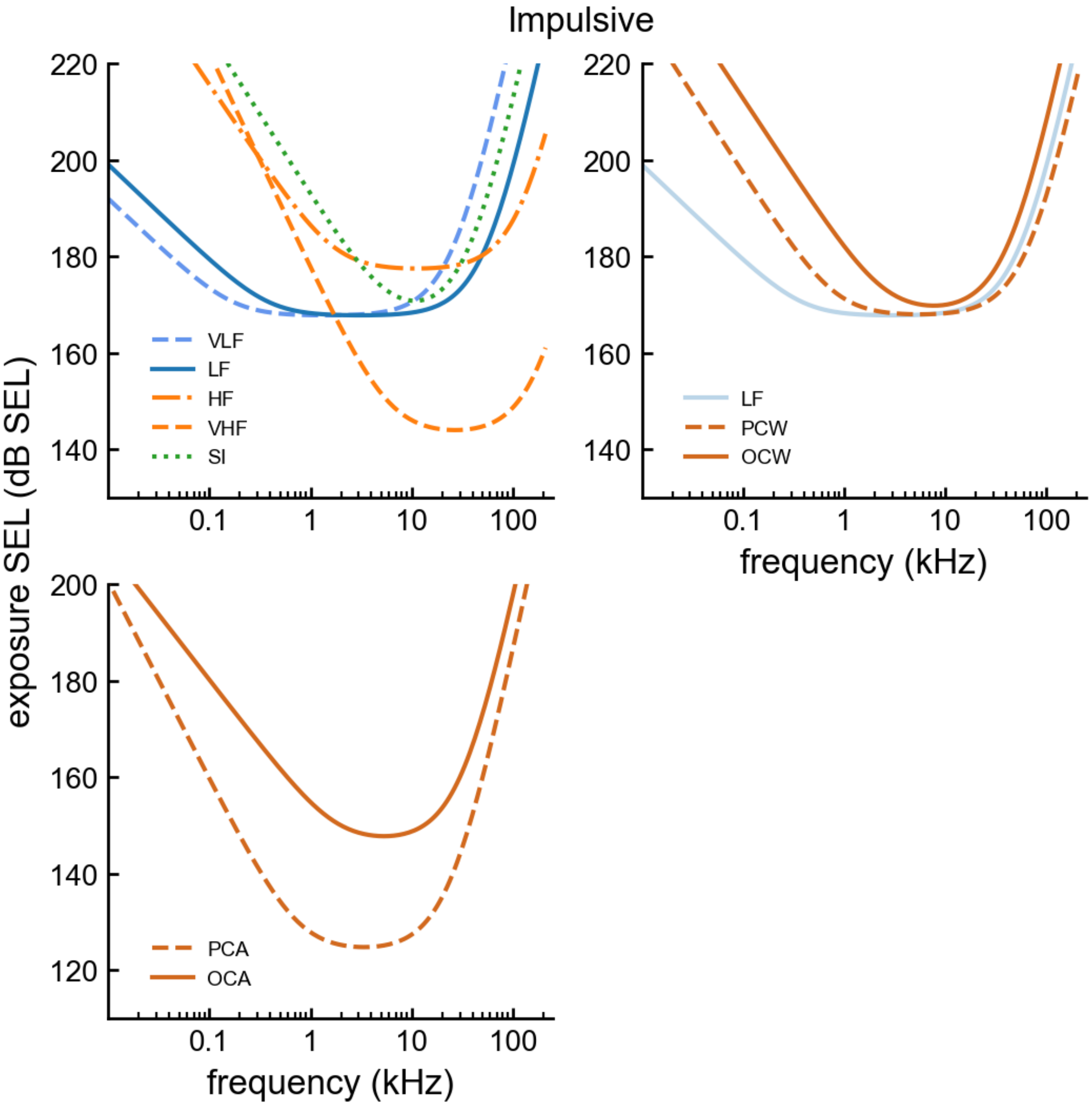


Figure 5. Comparison of Navy Phase 4 TTS exposure functions for explosives, impact pile driving, air guns, and other impulsive sources across species groups.

Table 3. Comparison of Phase 3 and Phase 4 TTS/AINJ peak SPL thresholds for explosives, impact pile driving, air guns, and other impulsive sources.

Group	TTS Phase 3	TTS Phase 4	INJ Phase 3	INJ Phase 4
VLF	213	216	219	222
LF	213	216	219	222
HF	224	224	230	230
VHF	196	196	202	202
OCW	226	224	232	230
PCW	212	217	218	223
SI	220	219	226	225
OCA	170	171	176	177
PCA	155	156	161	162

- Peak SPL thresholds are in dB re $1\mu\text{Pa}$ underwater and dB re $20\ \mu\text{Pa}$ in air (groups OCA and PCA only).

The most significant differences between the Phase 3 and Phase 4 functions and thresholds include the following:

(1) Mysticetes were divided into two groups (VLF and LF), with the upper hearing limit for the LF group increased from Phase 3 to match recent hearing measurements in minke whales (Houser et al., 2024).

(2) Group names were changed from Phase 3 to be consistent with Southall et al. (2019a). Specifically, the Phase 3 mid-frequency (MF) cetacean group is now designated as the high frequency (HF) cetacean group, and the group previously designated as high-frequency (HF) cetaceans is now the very-high frequency (VHF) cetacean group.

(3) For the HF group, Phase 4 onset TTS/AINJ thresholds are lower compared to Phase 3 at frequencies below 10 kHz. This results from new TTS onset data for dolphins at low frequencies (Finneran et al., 2023).

(4) For the PCW group, new TTS data for harbor seals (Kastelein et al., 2020b; Kastelein et al., 2020e) resulted in slightly lower TTS/AINJ thresholds at high frequencies compared to Phase 3.

(5) For group OCW, new TTS data for California sea lions (Kastelein et al., 2021b; Kastelein et al., 2022a; Kastelein et al., 2022b) resulted in significantly lower TTS/AINJ thresholds compared to Phase 3.

ES-2. MARINE MAMMAL BEHAVIORAL RESPONSE CRITERIA

This section describes the rationale and steps used to define criteria and numeric thresholds for predicting behavioral response thresholds for marine mammals exposed to non-impulsive sources (e.g., sonars and other active acoustic sources) and impulsive sources (e.g., explosives, pile driving, and air guns) for Phase 4. Since the derivation of Phase 3 behavioral response criteria and thresholds, new data have been obtained on the effects of noise on marine mammal behavior. Therefore, for Phase 4, criteria and thresholds for behavioral response have been updated.

Marine mammals were divided into four groups for analysis: mysticetes (all baleen whales), odontocetes (most toothed whales, dolphins, and porpoises), sensitive species (beaked whales and harbor porpoise), and pinnipeds (true seals, sea lions, walruses, sea otters, polar bears). These groups are like the groups used in the Phase 3 behavioral response analysis, with the exception of combining beaked whales and harbor porpoise into a single curve.

For each group, a biphasic behavioral response function was developed using the best available data and Bayesian dose response models developed at the University of St. Andrews. The behavioral response function base probability of response on the highest SPL root-mean-square (rms) received level. The behavioral response functions are as follows:

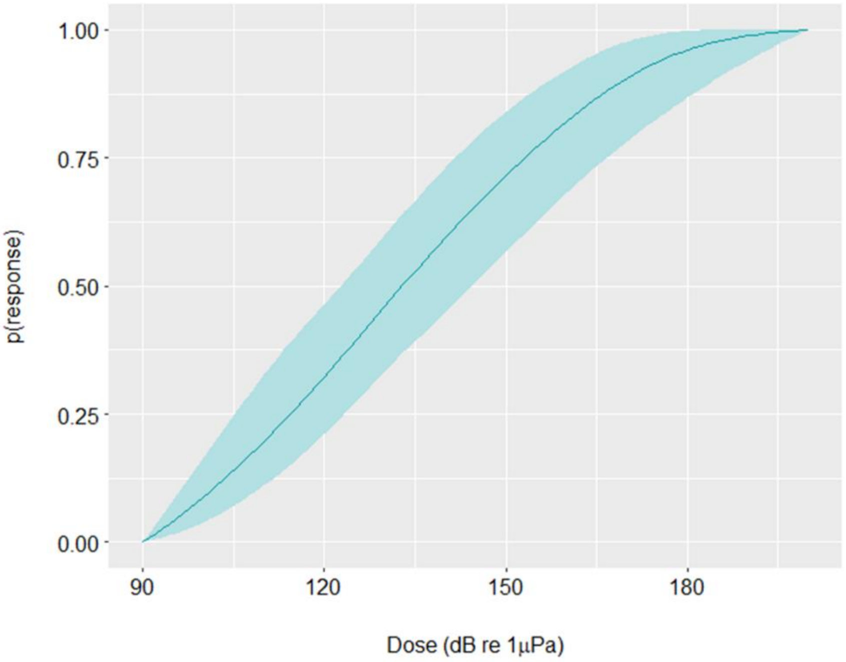


Figure 6. Phase 4 Sensitive Species Biphasic Behavioral Response Function.

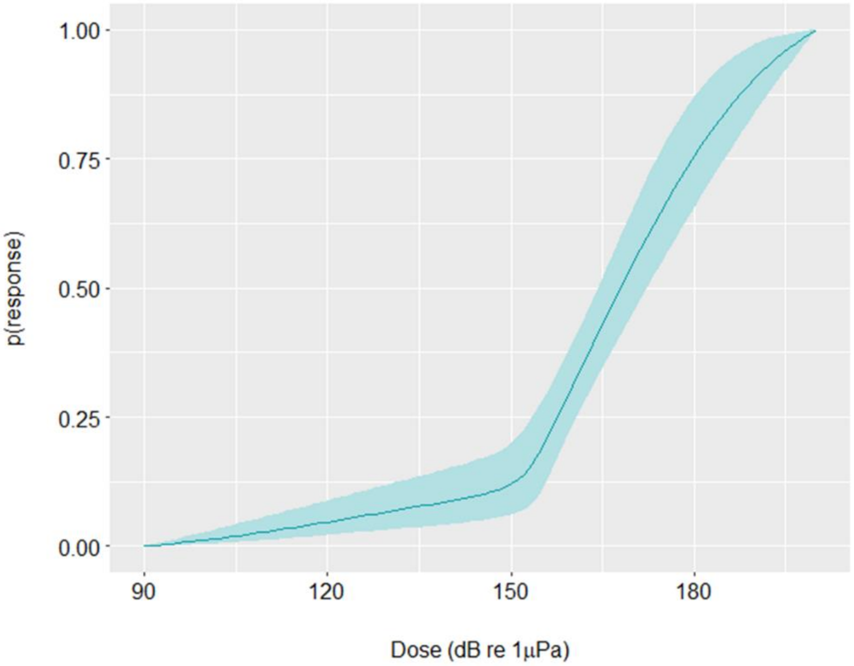


Figure 7. Phase 4 Odontocete Biphasic Behavioral Response Function.

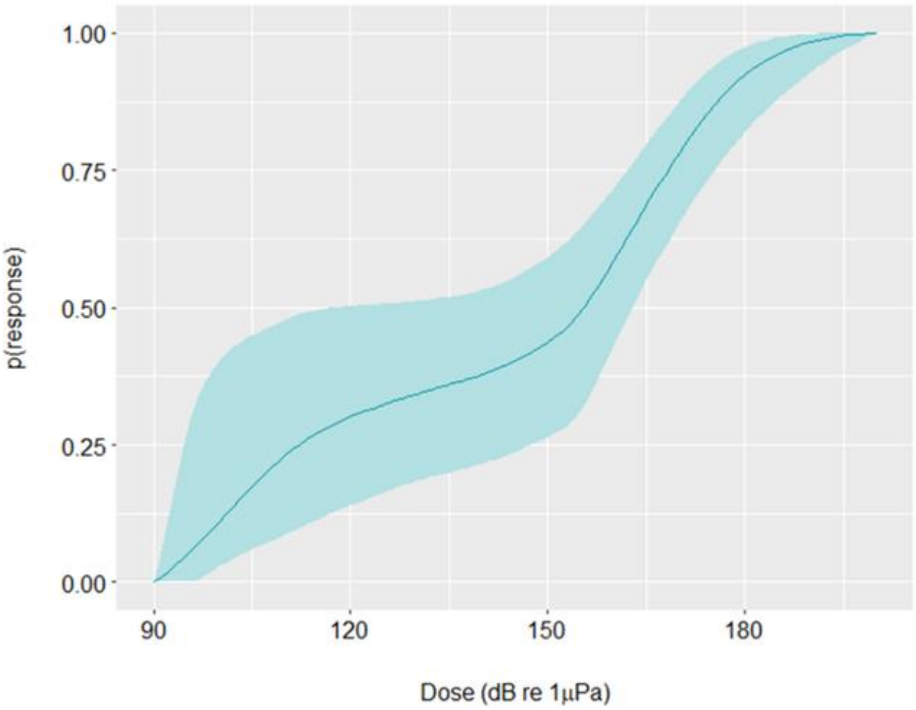


Figure 8. Phase 4 Pinniped (in Water) Biphasic Behavioral Response Function.

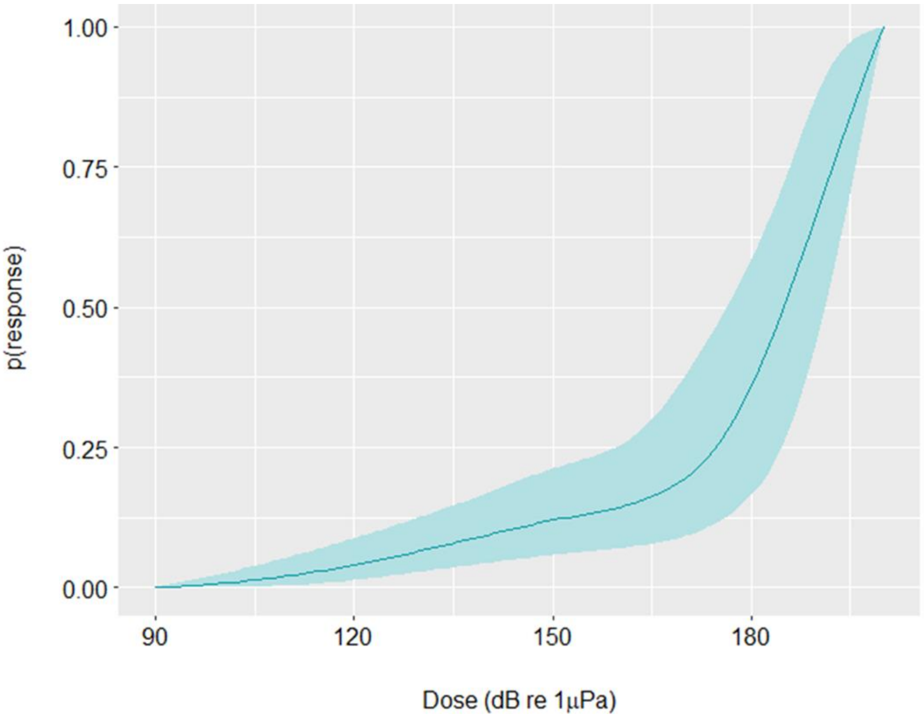
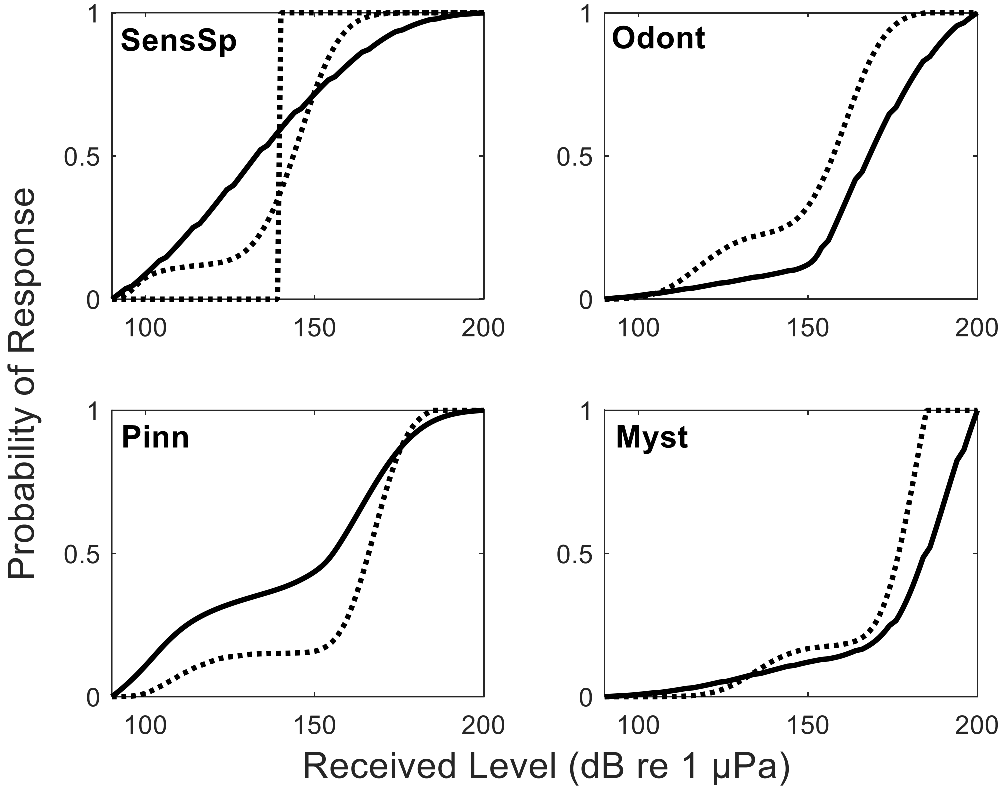


Figure 9. Phase 4 Mysticete Biphasic Behavioral Response Function.



- SensSp = Sensitive Species
- Odont = Odontocetes
- Pinn = Pinnipeds
- Myst = Mysticetes
- The Phase 3 beaked whale response function and the harbor porpoise step function are plotted against the Sensitive Species curve.

Figure 10. Behavioral Response Functions from Phase 3 (dashed lines) and Phase 4 (solid lines).

Due to the addition of new data and the separation of some species groups, the most significant differences between the Phase 3 and Phase 4 functions include the following:

- Harbor porpoises and beaked whales were combined into one curve.
- The Phase 4 sensitive species BRF is more sensitive at lower received levels but less sensitive at higher received levels than the Phase 3 BRF. The 50 percent point of the behavioral response function is 133 dB re 1 µPa, with response received levels for these species ranging from 95 to 138.4 dB re 1 µPa.
- The odontocete curve in Phase 4 is less sensitive than the odontocete curve from Phase 3. Response received levels for these species ranged from 94 to 185 dB re 1 µPa, with the 50 percent point of the curve occurring at 168 dB re 1 µPa.
- The Phase 4 pinniped in-water BRF shifted to the left because of the inclusion of additional captive pinniped data.
- The mysticete curve in Phase 4 is less sensitive at higher received levels than the general mysticete curve from Phase 3 due to the inclusion of more data at more received levels. The 50

percent probability level of this curve occurs at 185 dB re 1 µPa, while species responded at received levels ranging from 105 to 164.6 dB re 1 µPa.

There are still no data available for a pinniped in-air BRF. Responses for these species occurred at received levels ranging from 107 to 185 dB re 1 µPa, with a 50 percent level of 156 dB re 1 µPa.

Additionally, as in Phase 3, Phase 4 behavioral response criteria for estimating marine mammal impacts from sonar and other active transducers include cutoff conditions (Table 4). Phase 3 applied distance cut-offs for two conditions: (1) moderate source level, single platform events and (2) multiple platform or high source level events. For Phase 4, the distance cut-offs are updated based on observed responses. In addition, a received level condition is applied. Significant behavioral responses are assumed to be those occurring:

- Within the cut-off range at any p(response)
- Beyond the cut-off range at any p(response) above p(0.5)

Table 4. Phase 4 behavioral cutoff conditions for each species group.

Behavioral Group	Phase 4		Phase 3
	BRF p(0.5)	Cut-off Range (km)	Cut-off Range (km)
Sensitive Species	133 dB	40 km	25/50 (beaked whales) 20/40 (harbor porpoises)
Odontocete	168 dB	15 km	10/20
Mysticete	185 dB	10 km	10/20
Pinniped	156 dB	5 km	5/10

ES-3. SEA TURTLE AUDITORY CRITERIA AND THRESHOLDS

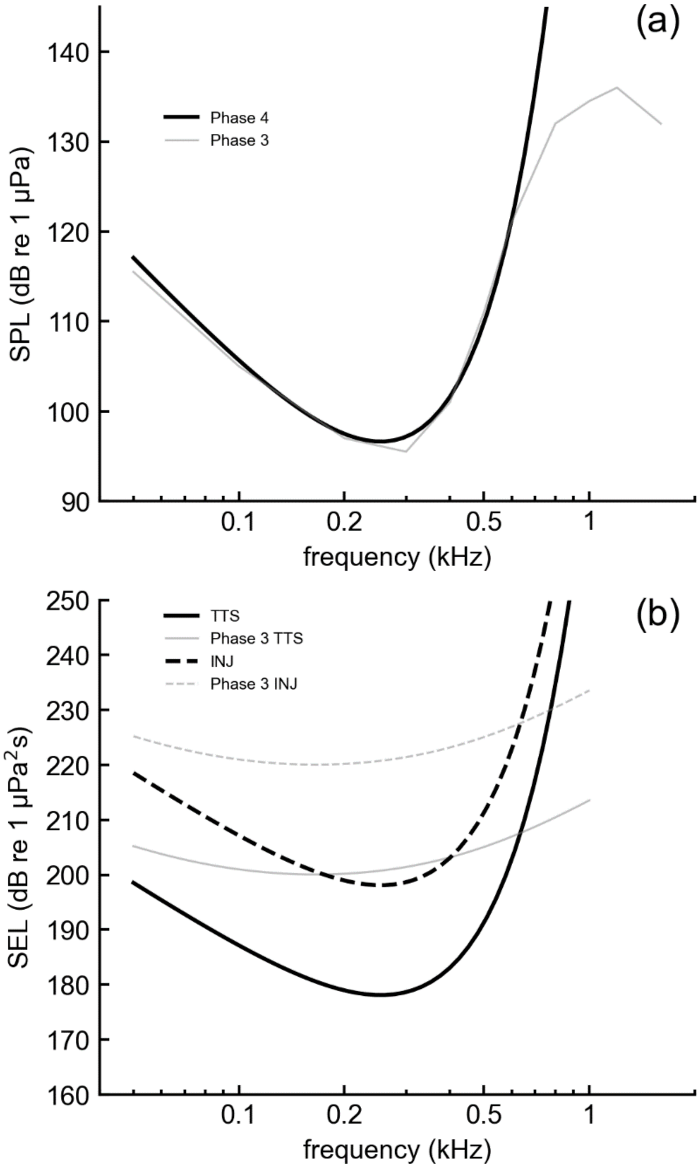
This section describes the rationale and steps used to define criteria and numeric thresholds for predicting auditory and behavioral effects on marine turtles exposed to non-impulsive acoustic sources (e.g., sonars and other active acoustic sources) and impulsive sources (e.g., explosives, pile driving, and air guns). Since the derivation of Phase 3 acoustic criteria and thresholds, new data have been obtained related to the effects of underwater noise on turtle hearing (Salas et al., 2023a, 2024). Therefore, for Phase 4, new criteria and thresholds for the onset of TTS and AINJ were developed utilizing the best available data (Table 5).

Table 5. Phase 3 and Phase 4 TTS and AINJ onset levels for sonar (non-impulsive) and explosive (impulsive) sound sources in sea turtles.

Source type and metric	Phase 3		Phase 4	
	TTS	AINJ (PTS ^{2})	TTS	AINJ
Non-impulsive onset SEL (weighted)^1	200	220	178	198
Impulsive onset SEL (weighted)	189	204	169	184
Impulsive onset Peak SPL	226	232	224	230

- For weighted SEL onsets, units are dB re $1\mu\mathrm{Pa}^2$ s.
- For impulsive peak SPL onsets units are dB re $1\mu\mathrm{Pa}$.
- [1] The weighted non-impulsive thresholds by themselves only indicate the TTS/AINJ threshold at the most susceptible frequency (the exposure function shape is shown in Figure 11b).
- [2] Auditory injury (AINJ) was previously referred to as permanent threshold shift (PTS). The new terminology acknowledges that auditory injury may occur without PTS.

A new sea turtle composite audiogram was derived from existing hearing data (Figure 11a). Based on the composite audiogram and TTS data from freshwater turtles, exposure functions were created for non-impulsive noise sources (Figure 11b).



- (a) Composite audiogram
- (b) Exposure functions for non-impulsive
- TTS (solid lines)
- AINJ (dashed lines)
- Phase 3 functions (thin gray lines)
- Phase 4 functions (thicker black lines)

Figure 11. Phase 4 comparison to Phase 3 for sea turtles (ST).

Although new data describing behavioral responses of sea turtles to noise have been published (Kastelein et al., 2023b), the SPL rms thresholds developed with NMFS for behavioral disturbance during Phase 3 are unchanged in Phase 4. For exposures to single and multiple explosions, SEL-based thresholds were developed that are consistent with the derivation of the marine mammal behavioral response thresholds to single and multiple explosions. A description of the best available science regarding behavioral response of sea turtles to noise is provided, along with the numeric thresholds (Table 6).

Table 6. Phase 4 behavioral response thresholds for sea turtles.

Source	dB SPL rms (unweighted)	dB SEL (cumulative; weighted)
Air guns	175	-
Pile driving	175	-
Sonar $\leq 2\text{kHz}$	175	-
Explosives	-	164

- Weighted cumulative SEL thresholds in dB re $1\mu\text{Pa}^2\ \text{s}$ and unweighted SPL rms thresholds in dB re $1\mu\text{Pa}$.
- The root mean square and sound exposure level calculations are based on the duration defined by the 5% and 95% points along the cumulative energy curve and captures 90% of the cumulative energy in the impulse.

ES-4. EXPLOSIVE NON-AUDITORY INJURY CRITERIA

Explosives in water can injure or kill marine mammals and sea turtles. Injury in this criteria context is distinct from auditory injury and refers to any other physical injury due to exposure to explosive energy.

This section describes the development of criteria and thresholds used to quantify recoverable injury and non-recoverable injury (presumed mortality) in mathematical modeling for the Phase 4 analyses. The Phase 4 criteria and thresholds are consistent with those applied in prior Navy analyses, although thresholds have been revised since Phase 3. In Phase 4, the thresholds are anchored to the lowest exposures with an effect observed in the underlying experimental data sets, rather than the means as in Phase 3. The Phase 4 approach is consistent with the lower thresholds applied in analyses preceding Phase 3 and is taken in consideration of the unique issues and limitations of the terrestrial animal data set used to develop these criteria.

Two metrics are used to assess injurious exposures to explosives: peak pressure and impulse. The impulse criterion relies on two variables: the mass of an animal (M) and its depth (D) below the water surface. The impulse is calculated over the lesser of the duration of the initial positive pressure or 20 percent of the estimated lung resonance period. Table 7 compares the Phase 3 and Phase 4 thresholds for mortality and injury.

Table 7. Comparison of Phase 3 and Phase 4 Mortality and Injury Thresholds for Explosives

Effect–Metric	Phase 3	Phase 4
Mortality–Impulse	$144M^{1/3}\left(1+\frac{D}{10.1}\right)^{1/6}$	$103M^{1/3}\left(1+\frac{D}{10.1}\right)^{1/6}\ \mathrm{Pa-s}$
Injury–Impulse	$65.8\left(1+\frac{D}{10.1}\right)^{1/6}$	$47.5M^{1/3}\left(1+\frac{D}{10.1}\right)^{1/6}\ \mathrm{Pa-s}$
Injury–Peak Pressure	243 dB re 1μ Pa peak	237 dB re 1μ Pa peak

D = depth in meters (m).

M = animal mass in kilograms (kg).

ACRONYMS

μPa	microPascal
μPa^{2}s	microPascal—squared—seconds
3S	Sea Mammals, Sonar, Safety
AEP	auditory evoked potential
AINJ	auditory injury
ASW	anti-submarine warfare
AUTEC	Atlantic Underwater Test and Evaluation Center
BRAHSS	Behavioural Response of Australian Humpback whales to Seismic Surveys
BRF	behavioral response function
BRS	behavioral response study
CAS	continuous active sonar
CDF	cumulative truncated normal distribution function
CEE	controlled exposure experiment
CES	controlled exposure study
C-Pods	cetacean and porpoise detector
CREEM	Centre for Research into Ecological and Environmental Modelling
cSEL	cumulative sound exposure level
D	depth
dB	decibel
DTAG	digital acoustic recording tag
EIS	environmental impact statement
ft	feet
FW	freshwater turtle
GAM	Generalized Additive Model
GAMM	Generalized Additive Mixed Model
GEE	Generalized Estimating Equation
GI	gastrointestinal
GLM	Generalized Linear Model
HELRAS	Helicopter Long-Range Active Sonar
HF	high frequency
HPAS	High Source Level Pulsed Sonar
Hz	hertz
kg	kilogram

kHz	kilohertz
km	kilometer
lb	pound
LF	low frequency
LFAS	low frequency Active Sonar
M	mass
m	meter
MF	mid-frequency
MFAS	Mid-Frequency Active Sonar
MMPA	Marine Mammal Protection Act
MPAS	Moderate Source Level Pulsed Sonar
Myst	mysticete
NAEMO	Navy Acoustic Effects Model
NFA	non-foraging active state
NITS	Noise-induced threshold shift
NMFS	National Marine Fisheries Service
OCA	otariid and other non-phocid marine carnivores in air
Odont	odontocete
ORBS	Off Range Beaked Whale Study
OCW	otariid and other marine carnivores in water
PAM	passive acoustic monitoring
PCA	phocid carnivores in air
PCW	phocid carnivores in water
Pinn	pinniped
PMRF	Pacific Missile Range Facility
Pp	peak to peak sound pressure level
PRN	pseudorandom noise
psi	pounds per square inch
PTS	permanent threshold shift
re	referenced
rms	root mean square
s	seconds
SEAMARCO	Sea Mammal Research Company
SEL	sound exposure level
SenSp	sensitive species

SI	sirenian
SOCAL	Southern California
SPL	sound pressure level
SRP	Scientific Research Program
ST	sea turtle
SURTASS	Surveillance Towed Array Sensor System
TM	tympanic membrane
T-PODS	a type of passive acoustic logger
TTS	temporary threshold shift
VHF	very high frequency
VLF	very low frequency
XHPAS	Extra High Source Level Pulsed Sonar

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APPENDICES

FIGURES

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1 INTRODUCTION

The United States (U.S.) Department of the Navy in cooperation with Joint Lead Agencies are required to assess the potential impacts on marine mammals and sea turtles from military readiness activities to maintain compliance with a suite of federal environmental laws and regulations. These regulations include, but are not limited to, the Marine Mammal Protection Act (MMPA), Endangered Species Act (ESA), and the National Environmental Policy Act (NEPA). In cases where these activities introduce sound or explosive energy into the marine environment, an acoustic effects analysis must be conducted. The effects analysis begins with mathematical modeling to predict the sound transmission patterns from acoustic and explosive sources. Activities that involve sonar and other transducers, air guns, pile driving, and explosives are modeled. 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 specific effects that animals exposed to sound may experience.

This report presents the criteria and thresholds applied in analyses of acoustic and explosive impacts on marine mammals and sea turtles for fourth phase of the US Navy's programmatic approach to environmental compliance at sea for ranges and operating areas. Previous development of criteria and thresholds occurred as part of Phase 2 (c. 2012) and Phase 3 (c. 2017). To remain consistent with prior terminology, the present criteria and thresholds are referred to as the "Phase 4" criteria and thresholds.

This report is comprised of four distinct sections that describe the derivation of criteria and thresholds used to predict specific effects. Specifically, these effects include auditory effects (see Section 2, Marine Mammal Auditory Weighting Functions and Exposure Functions and Section 4.1, Sea Turtle Auditory Weighting Functions and Exposure Functions), behavioral responses (see Section 3, Marine Mammal Behavioral Response Criteria, and Section 4.2, Sea Turtle Behavioral Response Thresholds), and non-auditory physiological impacts (see Section 5, Explosive Non-Auditory Injury Criteria). Appendix A provides the data used to develop marine mammal weighting functions and exposure functions, Appendix B describes the methods for estimating a low-frequency cetacean audiogram, and Appendix C describes marine mammal temporary threshold shift (TTS) growth curves. Appendix D list studies considered but not used in the development of the behavioral criteria, Appendix E lists data used to develop the marine mammal behavioral response functions, Appendix F lists seismic studies considered for impulsive behavioral response, and Append G explains model development and selection for the behavioral response functions.

Research on the impacts of anthropogenic sound on marine species has increased dramatically in the past decade. Since the methodologies for deriving composite audiograms, associated marine mammal auditory weighting functions, TTS/AINJ thresholds, and behavioral response functions are data driven, any new information that becomes available has the potential to cause some amount of change for a behavioral group or specific hearing group, as well as other hearing groups that rely on surrogate data. As such, the reported criteria and thresholds for marine mammals and sea turtles are anticipated to change over time; however, it is not feasible to make changes with the publication of each new data point. Instead, NIWC Pacific will periodically examine the best available science and consider the impacts of those studies on the criteria and thresholds, with an anticipated revision cycle of seven years. There may, however, be special circumstances that merit evaluation of data on a more accelerated timeline (e.g., the measurement of mysticete hearing thresholds).

2 MARINE MAMMAL AUDITORY WEIGHTING FUNCTIONS AND EXPOSURE FUNCTIONS

2.1 INTRODUCTION

2.1.1 Overview

This section describes the rationale and steps to define numeric thresholds for predicting auditory effects on marine mammals exposed to active sonars, other (non-impulsive) active acoustic sources, explosives, pile driving, air guns, and other impulsive acoustic sources for Navy acoustic effects analyses.

2.1.2 Impulsive vs. Non-impulsive Noise

When analyzing the auditory effects of noise exposure, it is often helpful to broadly categorize noise as either impulsive noise - noise with high peak sound pressure, short duration, and fast rise-time - or non-impulsive (i.e., steady-state) noise. When considering auditory effects, sonars, other coherent active sources, and vibratory pile driving are considered 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.

2.1.3 Noise-Induced Threshold Shifts and Auditory Injury

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).

A variety of terrestrial and marine mammal data sources (e.g., Finneran et al., 2007; Kastelein et al., 2013a; Kryter et al., 1966; Miller et al., 1963; Ward, 1960; Ward et al., 1958, 1959) indicate that NITSs up to 40 to 50 dB, measured a few minutes after exposure, may be induced without PTS. Therefore, an exposure producing an initial TTS of 40 dB can be considered a conservative upper limit for reversibility and any additional exposure could 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.

In some cases, intense noise exposures have caused auditory injury (AINJ, e.g., loss of cochlear neuron synapses), despite thresholds eventually returning to normal; i.e., it is possible to have AINJ without a resulting PTS (e.g., Fernandez et al., 2015; Houser, 2021; Kujawa, 2010; Kujawa & Liberman, 2006, 2009; Ryan et al., 2016).

In these situations, however, NITSs were 30–50 dB measured 24 h after the exposure; i.e., there is no evidence that an exposure resulting in < 40 dB TTS measured a few minutes after exposure can produce AINJ. Therefore, an exposure producing 40 dB of TTS, measured a few minutes after exposure, can also be used as an upper limit to prevent AINJ; i.e., it is assumed that exposures beyond those capable of causing 40 dB of TTS have the potential to result in AINJ (which may or may not result in PTS).

2.1.4 Onset TTS and Onset AINJ

Navy thresholds for predicting auditory effects of sound on marine animals focus on defining thresholds for the onset of TTS and AINJ (which includes, but is not limited to, PTS). In practice, it can be difficult to discern a "true" threshold elevation after noise exposure from typical variations in thresholds over time, therefore a TTS of 6 dB has been historically used to distinguish non-trivial amounts of TTS in marine mammals from fluctuations in threshold measurements that typically occur across test sessions (e.g., Ridgway et al., 1997; Schlundt et al., 2000; Southall et al., 2007a; Southall et al., 2019a). This is similar to the "standard threshold shift" concept applied to workplace hearing assessment (29 CFR 1910.95, 2008). Navy acoustic impact analyses therefore consider the onset of TTS to be 6 dB of TTS measured a few minutes (typ. 2–5 min) after exposure. Navy analyses assume that exposures resulting in a NITS ≥ 40 dB measured a few minutes after exposure may result in some amount of AINJ and/or residual PTS. A TTS of 40 dB is therefore used as a proxy for the onset of AINJ.

Sound levels just-capable of resulting in TTS or AINJ are referred to as "onset" levels; e.g., an exposure just-capable of producing TTS is referred to as the onset-TTS exposure. Onset levels are treated as step functions or "all-or-nothing" thresholds: exposures above the TTS or AINJ onset level are assumed to always result in TTS or AINJ, while exposures below the TTS or AINJ onset level are assumed to not cause TTS or AINJ.

2.1.5 Auditory Weighting Functions

Animals are not equally sensitive to noise at all frequencies. To capture the frequency-dependent nature of the effects of noise, US Navy acoustic impact analyses use auditory weighting functions. 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 sound level is calculated. The filters 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.

2.1.6 Phase 4 Weighting Functions and TTS/AINJ Thresholds

Weighting function derivation for Navy Phase 3 was consistent with the National Marine Fisheries Service Technical Guidance (National Marine Fisheries Service, 2016b, 2018; U.S. Department of the Navy, 2017). Marine mammal species were divided into groups for analysis. For each group, a frequency-dependent weighting function and numeric thresholds for the onset of TTS and AINJ were derived from available data describing hearing abilities and effects of noise on marine mammal hearing. 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 were available, the weighting function parameters were adjusted to provide the best fit to the experimental data. Extrapolation methods were then used to derive parameters for the groups for which TTS data did not exist.

Since the derivation of Phase 3 acoustic criteria and thresholds, new data have been obtained regarding marine mammal hearing and the effects of noise on marine mammal hearing (e.g., see Tougaard et al., 2022). As a result, new weighting functions and TTS/AINJ thresholds have been developed for Phase 4. Derivation of the new criteria and thresholds followed the same general approach utilized in Phase 3; however, some changes were made to accommodate new data, simplify the methodology, and align methods with recommendations from Southall et al. (2019a).

2.1.7 Use of Mean and Median

At various steps during weighting function derivation, the central tendency of a dataset is needed. Since the underlying data are often limited, it can be difficult to identify whether the mean (average) value or median (50th percentile) value is the most appropriate estimate for the central tendency. Therefore, by convention, Phase 4 analyses utilize the mean value, unless there is evidence that the distribution of the underlying data is skewed (i.e., not normally distributed) or outliers exist. In these situations, the use of the median is specifically noted.

2.2 WEIGHTING FUNCTIONS AND EXPOSURE FUNCTIONS

As in Phase 3, the Phase 4 auditory weighting function shapes are based on a generic band-pass filter defined by the equation

$$W(f) = C + 10\log_{10}\left\{\frac{(f/f_1)^{2a}}{[1+(f/f_1)^2]^a[1+(f/f_2)^2]^b}\right\} \tag{3}$$

where $W(f)$ is the weighting function amplitude (in dB) at the frequency f (in kHz). During implementation, the weighting function defined by Eq. (3) is used in conjunction with weighted thresholds for TTS and AINJ for non-impulsive and impulsive exposures, expressed in units of sound exposure level (SEL).

For developing and visualizing the effects of the various weighting functions, it is helpful to invert Eq. (3), yielding

$$E(f) = K - 10\log_{10}\left\{\frac{(f/f_1)^{2a}}{[1+(f/f_1)^2]^a[1+(f/f_2)^2]^b}\right\} \tag{4}$$

where $E(f)$ is the acoustic exposure level as a function of frequency f, the parameters f_1, f_2, a, and b are identical to those in Eq. (3), and K is a constant. The function described by Eq. (4) has a "U-shape" similar to an audiogram or equal loudness/latency contour (Figure 12 and13, right panels). K is defined to set the minimum value of $E(f)$ to match the weighted threshold for the onset of TTS or AINJ, for non-impulsive or impulsive exposures. Equation (4) therefore describes how the exposure level necessary to cause TTS or AINJ varies with frequency. The function defined by Eq. (4) is therefore referred to as an exposure function, since the curve defines the acoustic exposure that equates to onset TTS or AINJ as a function of frequency. There are four exposure functions (and thus four separate values for K) for each species group: non-impulsive exposure TTS and AINJ, and impulsive exposure TTS and AINJ.

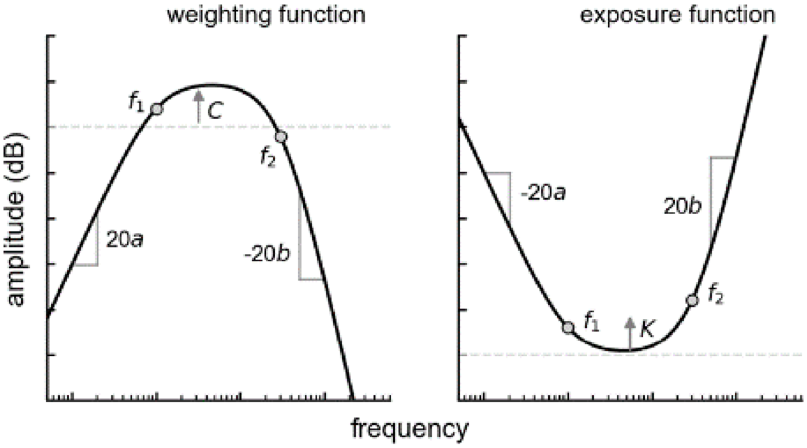
The shapes of the weighting function (Eq. 3) and exposure function (Eq. 4) are defined by the parameters C, K, f_1, f_2, a, and b (Figure 12 and Figure 13):

C *weighting function gain* (dB). The value of *C* defines the vertical position of the weighting function. 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).

K *exposure function gain* (dB). The value of *K* defines the vertical position of the exposure function. Changing the value of *K* shifts the function up/down. The value of *K* is chosen to set the minimum amplitude of *E* to match the weighted threshold value. For each species group, separate values of *K* will exist for TTS (K_{TTS}) and injury (K_{AINJ}) for non-impulsive and impulsive sounds.

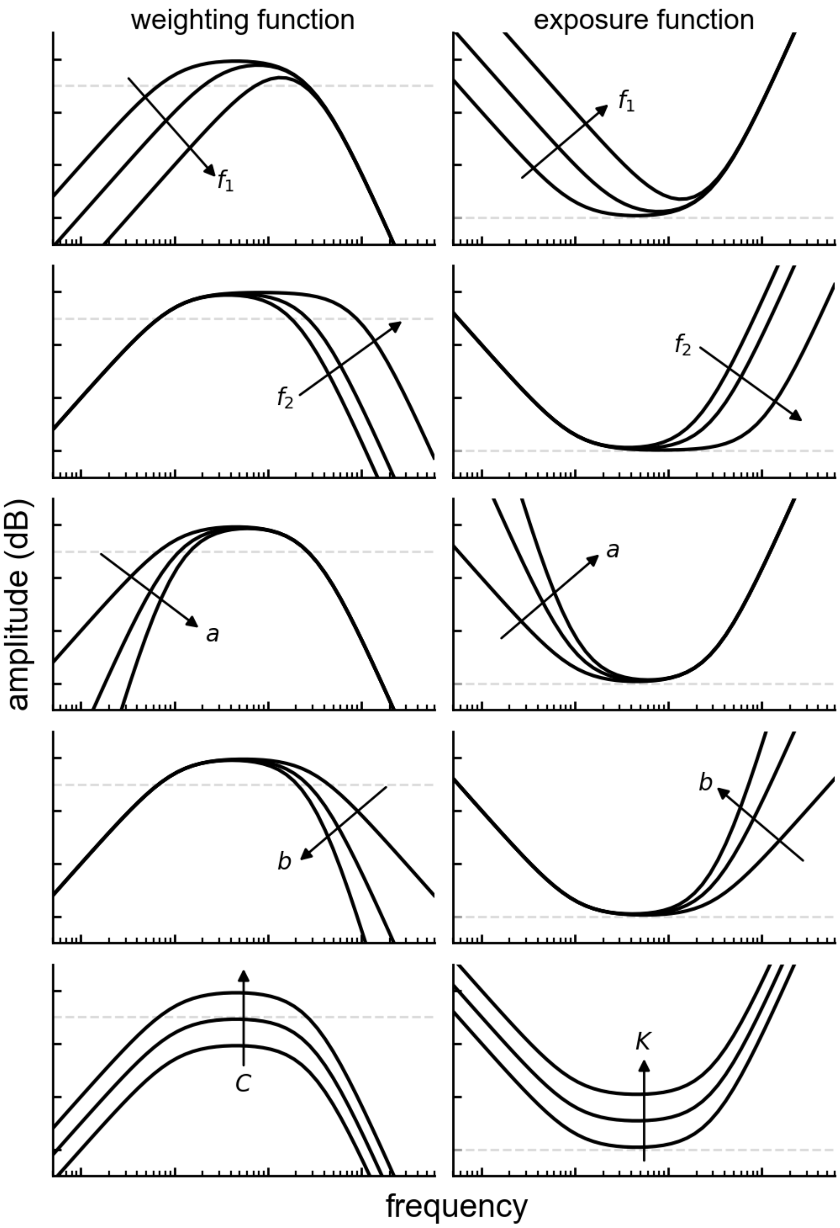
f_1 *low-frequency cutoff* (kHz). The value of f_1 defines the lower limit of the filter pass-band; i.e., the lower frequency at which the weighting function amplitude begins to decline or “roll-off” from the flat, central portion of the curve. The specific amplitude at f_1 depends on the value of a. 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 weighting function amplitudes at f_1 and steeper roll-offs 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 weighting function amplitudes at f_2 and steeper roll-offs at frequencies above f_2.



- 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 12. Examples of (left) weighting function amplitude described by Eq. (3) and (right) exposure function amplitude described by Eq. (4).



- The arrows indicate the direction of change when the designated parameter is increased.

Figure 13. Influence of parameter values on the resulting shapes of the weighting and exposure functions.

2.3 METHODOLOGY TO DERIVE FUNCTION PARAMETERS

Weighting and exposure functions are defined by selecting appropriate values for $C, K, f_1, f_2, a,$ and b in Eqs. (3) and (4). Ideally, parameters for each group would be selected as those values resulting in the "best-fit" of Eq. (4) to experimental data describing the onset of TTS/AINJ over a range of exposure frequencies, species, and individual subjects within that group. Data for the frequency-dependency of TTS in marine mammals exist, however they are limited at present, and there are no data showing frequency dependency of AINJ in marine mammals. Therefore, in addition to TTS data, weighting and exposure function derivations also utilized auditory threshold measurements (audiograms), equal latency contours, and anatomical predictions of sensitivity.

For Phase 4, marine mammal species were divided into nine groups based on auditory, ecological, and phylogenetic relationships among species and the medium (air or water) in which they could be exposed. For each group, exposure/weighting functions and weighted thresholds were derived for impulsive and non-impulsive exposures. For the species groups containing sufficient data, TTS exposure functions were directly fit to the TTS data. The relationships between the exposure functions and audiogram shapes for these groups were then used as a basis for extrapolation to the other groups. This extrapolation relied on an assumption that TTS exposure functions would resemble the audiogram, but would show less change with frequency compared to audiograms.

Table 8 lists the steps for function parameter derivation in Phase 4 and compares them to those used in Phase 3.

Table 8. Steps used to define weighting and exposure function parameters for Phase 3 and Phase 4.

Step	Phase 3	Phase 4
1	Marine mammal species were divided into groups.	
2	For each group, a representative, composite audiogram was estimated.	
3	The exponent a was defined as the smaller of the low frequency slope from the audiogram and equal latency contour.	
4	The exponent b was set equal to two.	The exponent b was set equal to five.
5	f_1 and f_2 were defined as the frequencies where composite audiogram thresholds were ΔT-dB above the lowest threshold. For groups with sufficient onset TTS data, the optimum value of ΔT was found by adjusting ΔT to best-fit Eq. (4) to the non-impulsive TTS onset data. This value of ΔT was used for the remaining groups. The parameter K was then adjusted to fit Eq. (4) to available or estimated TTS onset data.	For groups with sufficient onset TTS data (delphinids, porpoises, otariids in water, and phocids in water), the parameters f_1, f_2, and K were adjusted to fit Eq. (4) to the non- impulsive TTS onset data. If the resulting exposure function bandwidth, defined as 10 dB above the minimum TTS onset value, did not meet or exceed that of the composite audiogram, f_1 was decreased and/or f_2 increased as necessary to ensure that the 10-dB bandwidth criterion was met. For the remaining groups, f_1 and f_2 were defined so the differences between the audiogram thresholds at f_1 and f_2 and the minimum threshold (ΔT_1 and ΔT_2, respectively) matched the median value of ΔT_1 and mean value of ΔT_2 for the delphinids, porpoises, otariids in water, and phocids in water in water. The parameter K was then adjusted to fit Eq. (4) to available or estimated TTS onset data.
6	The non-impulsive, weighted TTS threshold was defined as the minimum of the TTS exposure function.	
7	The parameter C was defined to set the peak amplitude of the weighting function to zero.	
8	The non-impulsive, weighted AINJ threshold was found by adding a constant value (20 dB) to the weighted TTS thresholds.	
9	For groups with impulse TTS onset data, weighted SEL and peak SPL TTS thresholds for explosives and other impulsive sources were obtained from the available impulse TTS data. Weighted SEL and peak SPL AINJ thresholds were estimated from the onset TTS thresholds. 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 groups with data. Peak SPL thresholds were estimated using the relationship between hearing thresholds and the impulse TTS peak SPL thresholds for the groups with data.	

2.4 MARINE MAMMAL SPECIES GROUPS

Marine mammals were divided into nine groups (Table 9), with the same weighting function and TTS/AINJ 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., Finneran & Jenkins, 2012; Ketten, 2000; National Marine Fisheries Service, 2018; Southall et al., 2007a; Southall et al., 2019a). In Navy Phase 3 analyses, all mysticetes were placed in a single hearing group, designated "low-frequency (LF) cetaceans." However, recent hearing measurements in minke whales (Houser et al., 2024) support separating mysticetes into two hearing groups, designated as "very-low frequency (VLF) cetaceans" and "low-frequency (LF) cetaceans." Splitting the mysticetes in such a way, and the categorization of the various species into the two groups (Table B-1, Appendix B), follows the recommendations of Southall et al. (2019a).

2.4.1 Very-Low-Frequency Cetaceans (Group VLF)

The VLF cetacean group contains the larger mysticetes (baleen whales): blue, fin, right, and bowhead whales. Although there have been no direct measurements of hearing sensitivity in these larger mysticetes, an audible frequency range of approximately 10 Hz to 30 kHz has been estimated from measured vocalization frequencies, observed reactions to playback of sounds, and anatomical analyses of the auditory system.

2.4.2 Low-Frequency Cetaceans (Group LF)

The LF cetacean group contains the mysticete species not included in the VLF group (e.g., minke, humpback, gray, pygmy right whales). The upper frequency limit of hearing has been estimated in a minke whale from direct measurements of auditory evoked potentials (AEPs) (Houser et al., 2024).

2.4.3 High Frequency Cetaceans (Group HF)

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

2.4.4 Very High Frequency Cetaceans (Group VHF)

The VHF 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. VHF cetaceans generally possess a higher upper-frequency limit and better sensitivity at higher frequencies than HF cetacean species.

2.4.5 Sirenians (Group SI)

The sirenian group contains manatees and dugongs. Behavioral and AEP threshold measurements for manatees have revealed lower upper-cutoff frequencies and lower sensitivities (higher thresholds) compared to the HF cetaceans.

2.4.6 Phocid Carnivores (Groups PCA, PCW)

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. Since these animals are amphibious, weighting functions and TTS/AINJ thresholds are included for airborne (group PCA) and underwater exposure (group PCW). Aerial and underwater hearing thresholds exist for some Northern Hemisphere species in this group. There is emerging evidence suggesting that a natural division may exist within the family Phocidae, with species within the subfamily Monachinae having lower hearing sensitivity and less susceptibility to noise compared to the subfamily Phocinae (Kastak et al., 2005; Sills et al., 2021); however, data exist from only single individuals from two Monachid species and there is insufficient knowledge to justify separation into two groups at this time.

2.4.7 Otariids and Other Non-Phocid Marine Carnivores (Groups OCA, OCW)

This group contains all eared seals (fur seals and sea lions), walruses (Odobenidae), sea otters (Mustelidae), and polar bears (Ursidae). 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 (see Figure A-1, Appendix A). Aerial and underwater hearing thresholds exist for some Northern Hemisphere species in this group. Separate weighting functions and TTS/AINJ thresholds are included for airborne (group OCA) and underwater exposure (group OCW).

Table 9. Marine mammal species group designations for Navy Phase 4 auditory weighting functions.

Code	Name	Members
VLF	Very low frequency cetaceans	Balaenidae (right and bowhead whales): *Eubalaena* spp., *Balaena* Balaenopteridae: *Balaenoptera physalus* (fin whale), *B. musculus* (blue whale)
LF	Low frequency cetaceans	Balaenopteridae: *Balaenoptera acutorostrata* (common minke whale), *B. bonaerensis* (Antarctic minke whale), *B. borealis* (sei whale), *B. edeni* (Bryde's whale), *B. omurai* (Omura's whale), *B. ricei* (Rice's whale), *Megaptera novaeangliae* (humpback whale) Eschrichtiidae (gray whale): *Eschrichtius* Neobalenidae (pygmy right whale): *Caperea*
HF	High frequency cetaceans	Physeteridae (sperm whale): *Physeter* Ziphiidae (beaked whales): *Berardius* spp., *Hyperoodon* spp., *Indopacetus*, *Mesoplodon* spp., *Tasmacetus*, *Ziphius* Delphinidae (killer whale, melon-headed whale, false/pygmy killer whale, pilot whales, some dolphin species): *Orcinus*, *Delphinus*, *Feresa*, *Globicephala* spp., *Grampus*, *Lagenodelphis*, *Lagenorhynchus acutus*, *L. albirostris*, *L. obliquidens*, *L. obscurus*, *Lissodelphis* spp., *Orcaella* spp., *Peponocephala*, *Pseudorca*, *Sotalia* spp., *Sousa* spp., *Stenella* spp., *Steno*, *Tursiops* spp.
VHF	Very high frequency cetaceans	Delphinidae (some dolphin species): *Cephalorhynchus* spp.; *Lagenorhynchus cruciger*, *L. austrailis* Phocoenidae (porpoises): *Neophocaena* spp., *Phocoena* spp., *Phocoenoides* Iniidae (Amazon river dolphin): *Inia* Kogiidae(Pygmy/dwarf sperm whale): *Kogia* Lipotidae (Baiji): *Lipotes* Pontoporiidae (La Plata dolphin): *Pontoporia*
SI	Sirenians	Trichechidae (manatees): *Trichechus* spp. Dugongidae (dugongs): *Dugong*
OCW OCA	Otariids and other non-phocid marine carnivores (water) Otariids and other non-phocid marine carnivores (air)	Odobenidae (walrus): *Odobenus* Otariidae (fur seals and sea lions): *Arctocephalus* spp., *Callorhinus*, *Eumetopias*, *Neophoca*, *Otaria*, *Phocarctos*, *Zalophus* spp. Mustelidae (sea/marine otter): *Enhydra*, *Lontra feline* Ursidae (polar bear): *Ursus maritimus*
PCW PCA	Phocids (water) Phocids (air)	Phocidae (true seals): *Cystophora*, *Erignathus*, *Halichoerus*, *Histriophoca*, *Hydrurga*, *Leptonychotes*, *Lobodon*, *Mirounga* spp., *Monachus*, *Neomonachus*, *Ommatophoca*, *Pagophilus*, *Phoca* spp., *Pusa* spp.

2.5 COMPOSITE AUDIOGRAMS

Composite audiograms for each species group were determined by 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 all marine mammal groups except (V)LF cetaceans, only behavioral (i.e., 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 overestimate thresholds and, therefore, overestimate the low-frequency slope of the audiogram.

   For (V)LF cetaceans, for which no behavioral or AEP threshold data exist, hearing thresholds were estimated by synthesizing predictions from suprathreshold AEP measurements, anatomical measurements and mathematical models of hearing, and animal vocalization frequencies (see Appendix B).

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, typically the earlier published data were used, when the individual was younger and less likely to exhibit age-related hearing loss. In some cases, data judged to be more representative or of higher quality were used, or data at overlapping frequencies were averaged. These cases are noted in Appendix A, Table A-1 and Table A-2.
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 auditory masking or hearing loss) were excluded.

Table A-1 (Appendix A) lists the individual audiogram data ultimately used to construct the composite audiograms (for all species groups except the LF cetaceans). Table A-2 lists the data that were excluded, along with the rationale for exclusion.

In contrast to Phase 3, where composite audiograms were derived using the original (absolute) threshold values and normalized threshold values, composite audiograms are only derived in Phase 4 using the actual threshold data (not normalized). Normalized audiograms are excluded in Phase 4 to simplify the analysis and to avoid inherent problems in normalizing datasets that do not contain the frequency region of best sensitivity.

Combining individual datasets requires a common set of frequency values. Therefore, frequency values for each individual were replaced with frequencies spaced at 1/12-octave intervals, encompassing the range of frequencies present in the original data. Threshold values at the 1/12-octave frequencies were obtained by linear-log interpolation (linear thresholds, logarithmic frequencies) between sequential data points. Figure 14 shows an example of the interpolation process.

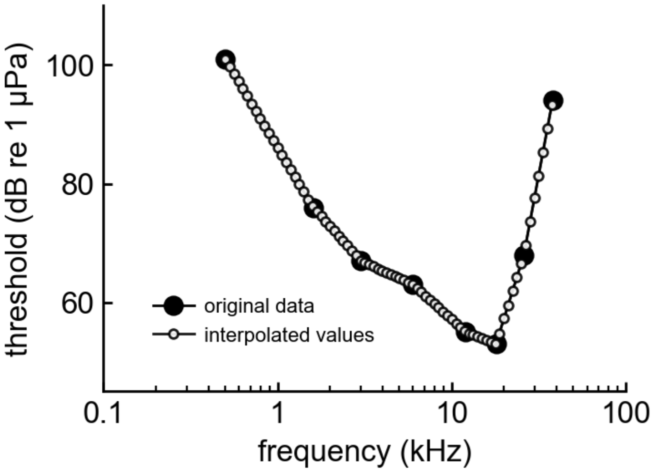


Figure 14. Interpolation process used to create a common set of frequency values.

To ensure common frequencies across studies, threshold data for each study were interpolated onto a grid of frequencies, logarithmically spaced at 1/12-octave intervals.

From these data, the median threshold value was calculated at each frequency and fit by the function

$$T(f) = T_0 + A\log_{10}\left(1 + \frac{F_1}{f}\right) + \left(\frac{f}{F_2}\right)^B \tag{5}$$

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. (5) was chosen to provide linear-log roll-off with variable slope at low frequencies and a steep rise at high frequencies. Equation (5) was fit to the median threshold data using the *curve fit* function in the optimize module of the Python package SciPy (Virtanen et al., 2020).

For Phase 4, composite audiograms were derived using the median value of the individual threshold data (as in Phase 3). From a statistical perspective, it would be better first to compute the median threshold for each species, and then compute the overall median value for each group from the species' medians. This would prevent a species from being over-represented in the final median value. In practice, however, this approach is more sensitive to the quality of individual audiograms, especially when the number of species is small. This is illustrated in Figure A-2, which compares composite audiograms derived using the two methods.

The resulting fitting parameters and goodness of fit values (R^2) are provided in Table 10. Because of the large number and possible high dependency of fitting parameters, in some cases, the specific fitting parameter values may not make physical sense (e.g., HF group F_1 = 9910 kHz); the important point is how well the resulting curve fits the median threshold data. Equation (5) 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 B for details).

Figure 15 shows the threshold data and composite audiograms based on the fitted curve for each species group. The composite audiograms for each species group are compared to each other in Figure 16, and the Phase 3 audiograms in Figure 17.

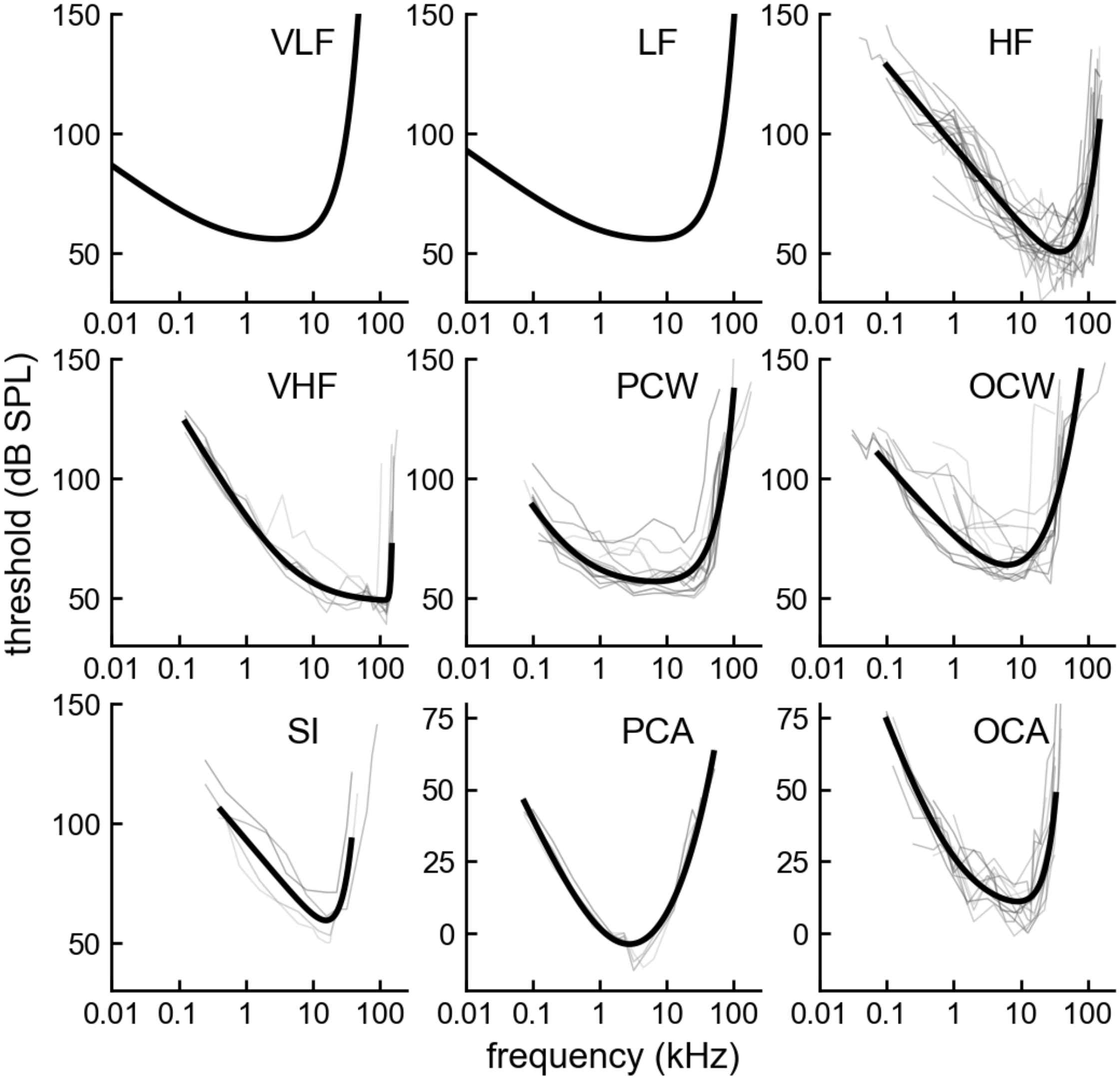
From the composite audiograms, the frequency of the lowest threshold, F_0, and the slope at the lower frequencies (over a 3-octave span), were calculated (Table 10 and Table 11).

Table 10. Composite audiogram parameter values for use in Eq. (5).

Group	T_0 (dB)	F_1 (kHz)	F_2 (kHz)	A	B	R^2	F_0 (kHz)	Min Thresh (dB SPL)
VLF	54.2	0.412	3.73	20.0	1.79	-	2.82	56
LF	54.2	0.880	7.97	20.0	1.79	-	5.96	56
HF	-38.9	9910	10.5	33.5	1.66	0.979	38.5	51
VHF	48.2	4.95	132	46.8	24.5	0.994	117	49
OCW	9.90	74.0	0.170	33.3	0.786	0.938	6.17	64
PCW	55.1	0.391	8.56	48.4	1.79	0.954	6.67	57
SI	-13.7	1680	7.87	33.1	2.52	0.996	15.6	59
OCA	6.90	1.04	8.86	63.7	2.78	0.990	9.00	11
PCA	-36.2	2.38	0.0188	52.6	0.581	0.976	2.73	-3.8

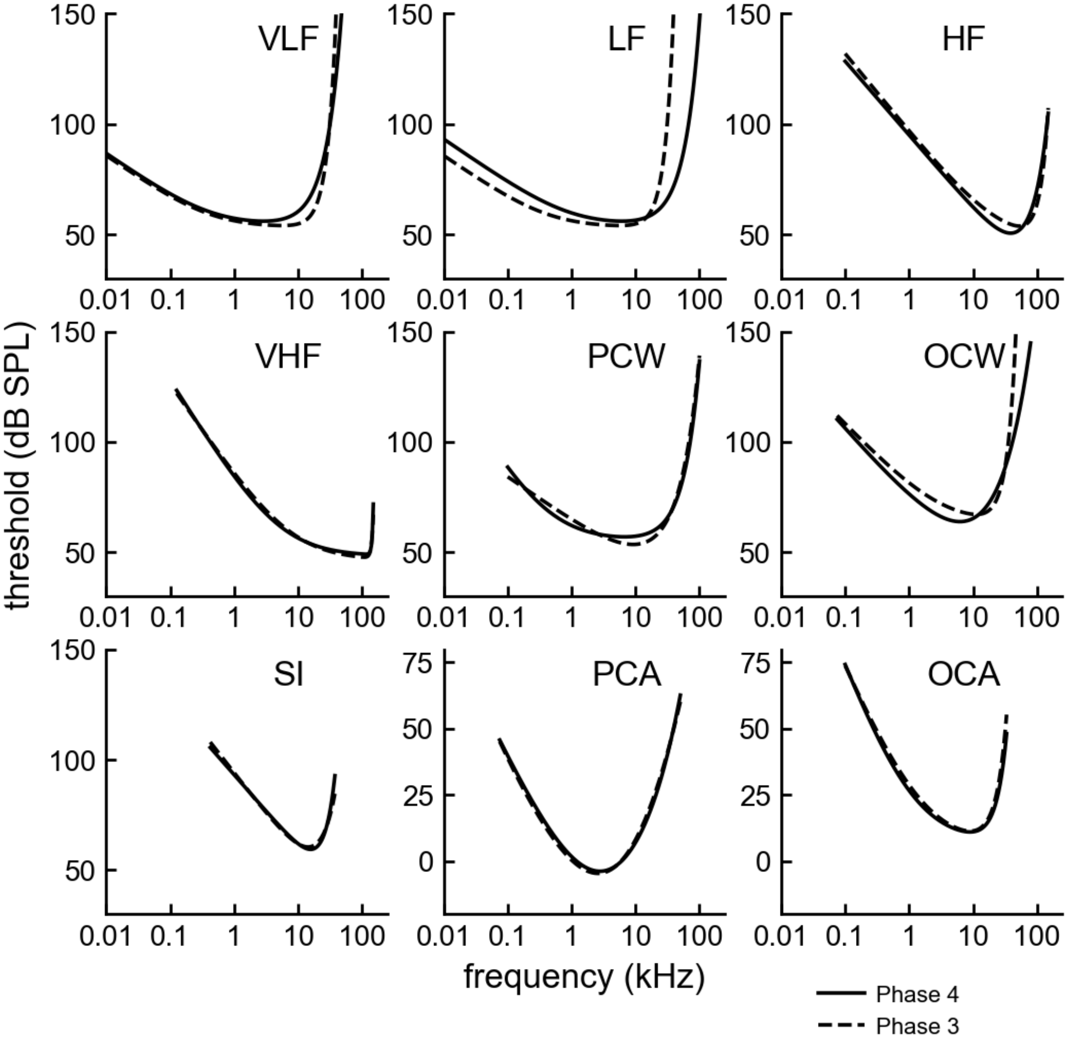
For all groups except VLF and LF cetaceans, values represent the best-fit parameters from fitting Eq. (5) to median values derived from experimental threshold data. For the VLF and LF cetaceans, Eq. (5) parameter values were estimated as described in Appendix B. The parameter F_0 is the frequency corresponding to the minimum threshold (Min Thresh). Min Thresh has units of dB re 1 µPa for underwater groups and dB re 20 µPa for in-air groups (OCA and PCA only).

Appendix A lists the individual audiograms used to derive the composite functions. Derivation of the VLF and LF cetacean curves is described in Appendix B.



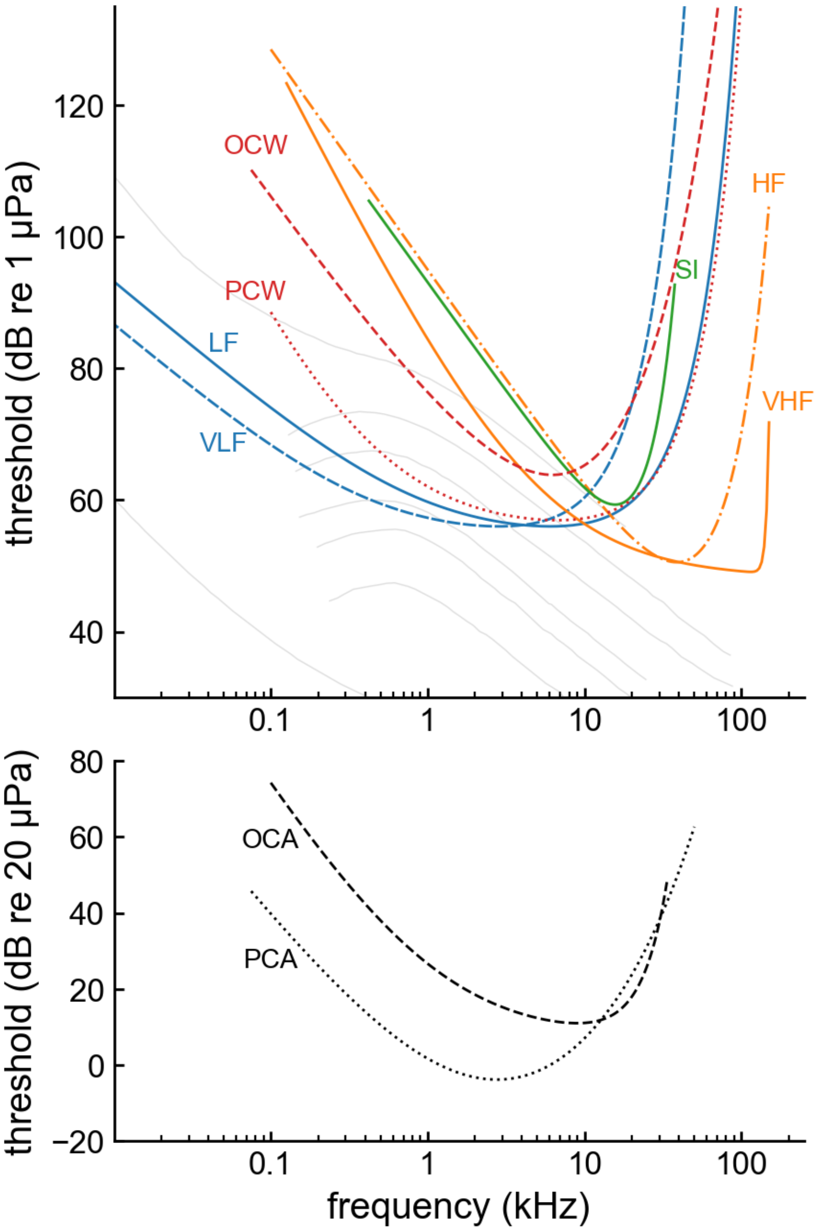
- Thin lines represent the threshold data from individual animals.
- Thick lines represent Phase 4 composite audiograms.
- Thresholds are expressed in dB re $1 \mu\mathrm{Pa}$ for underwater data and dB re $20\ \mu Pa$ for in-air data (groups OCA and PCA only).

Figure 15. Thresholds and composite audiograms for the marine mammal species groups.



- Thresholds are expressed in dB re $1\ \mu\mathrm{Pa}$ for underwater data and dB re $20\ \mu\mathrm{Pa}$ for in-air data (groups OCA and PCA only).

Figure 16. Comparison of Phase 3 and Phase 4 composite audiograms.



- The thin (gray) lines in the upper panel represent ambient noise spectral density levels (referenced to the left ordinate, but in dB re 1 μPa^2/Hz corresponding to the limits of prevailing noise (upper and lower traces) and various sea-state conditions, from 0.5 to 6 (National Research Council (NRC), 2003).

Figure 17. Composite audiograms for the various species groups underwater (upper) and in-air (lower).

Table 11. Frequency of best hearing (F_0) and the magnitude of the low-frequency slope derived from composite audiograms (Aud. slope) and equal latency contours (Eq. lat. slope).

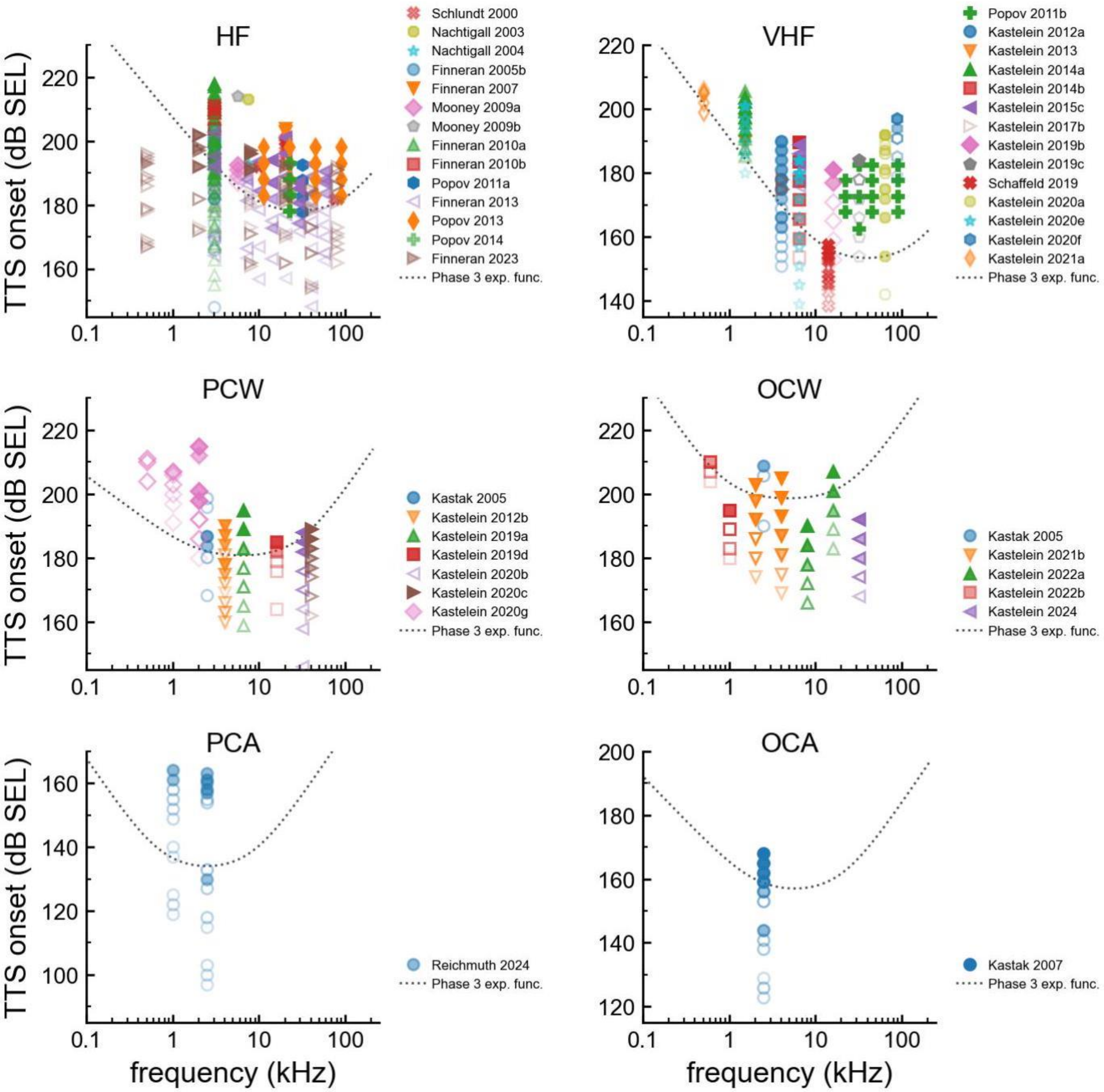
Group	F_0 (kHz)	Aud. slope (dB/dec)	Eq. lat. slope (dB/dec)
VLF	2.82	20	-
LF	5.96	20	-
HF	38.5	34	31
VHF	117	45	50
OCW	6.17	32	-
PCW	6.67	33	-
SI	15.6	33	-
OCA	9.00	55	27
PCA	2.73	45	41

- Audiogram slopes were calculated across a frequency range of 3 octaves beginning with the lowest frequency present for each group.
- Equal latency slopes were calculated from the available equal latency contour data (Mulsow et al., 2015; Reichmuth, 2013; Wensveen et al., 2014).

2.6 TTS DATA REVIEW

2.6.1 Non-Impulsive (Steady-State) Exposures – TTS Onset

Figure 18 shows the non-impulsive TTS data available for each marine mammal group. The symbol style indicates the amount of TTS produced by that combination of exposure frequency and SEL: open symbols, TTS < 6 dB; filled symbols, TTS ≥ 6 dB; transparency indicates the relative amount of TTS (less transparent means larger TTS).



- Open symbols indicate combinations of exposure frequency and SEL that resulted in < 6 dB of mean TTS.
- Filled symbols indicate combinations of exposure frequency and SEL that resulted in ≥ 6 dB of mean TTS.
- The transparency of each symbol indicates the relative amount of TTS; i.e., less transparent symbols indicate more TTS. Units for TTS onset are dB re $1\ \mu\text{Pa}^2\text{s}$ in water (groups HF, VHF, PCW, OCW) and re $20\ \mu\text{Pa}^2\text{s}$ in air (groups OCA, PCA).

Figure 18. Summary of available TTS data for each marine mammal group.

The most critical data for weighting and exposure function derivation are TTS onset exposure levels as a function of exposure frequency—for species groups with sufficient data, the parameters in Eq. (4) are adjusted so the exposure function matches these TTS onset data. TTS onset values are estimated from published literature by examining TTS as a function of SEL for various frequencies. As in Phase 3, only TTS data from psychophysical (behavioral) hearing tests were used (U.S. Department of the Navy, 2017; National Marine Fisheries Service, 2016a, 2018; Southall et al., 2019a).

To determine TTS onset for each subject, the amount of TTS observed after exposures with different SPLs and durations (Figure 18) 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 may 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 has often produced more TTS (e.g., Finneran et al., 2010a; Kastak et al., 2007; Mooney et al., 2009b). Despite these limitations, the equal energy rule is still a useful concept because 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).

Marine mammal TTS studies have shown that TTS generally 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 generally become steeper and approach linear relationships with the noise SEL. Accordingly, most TTS growth data were fit with the function

$$t(L) = m_1 \log_{10}\left[1 + 10^{(L-m_2)/10}\right] \tag{6}$$

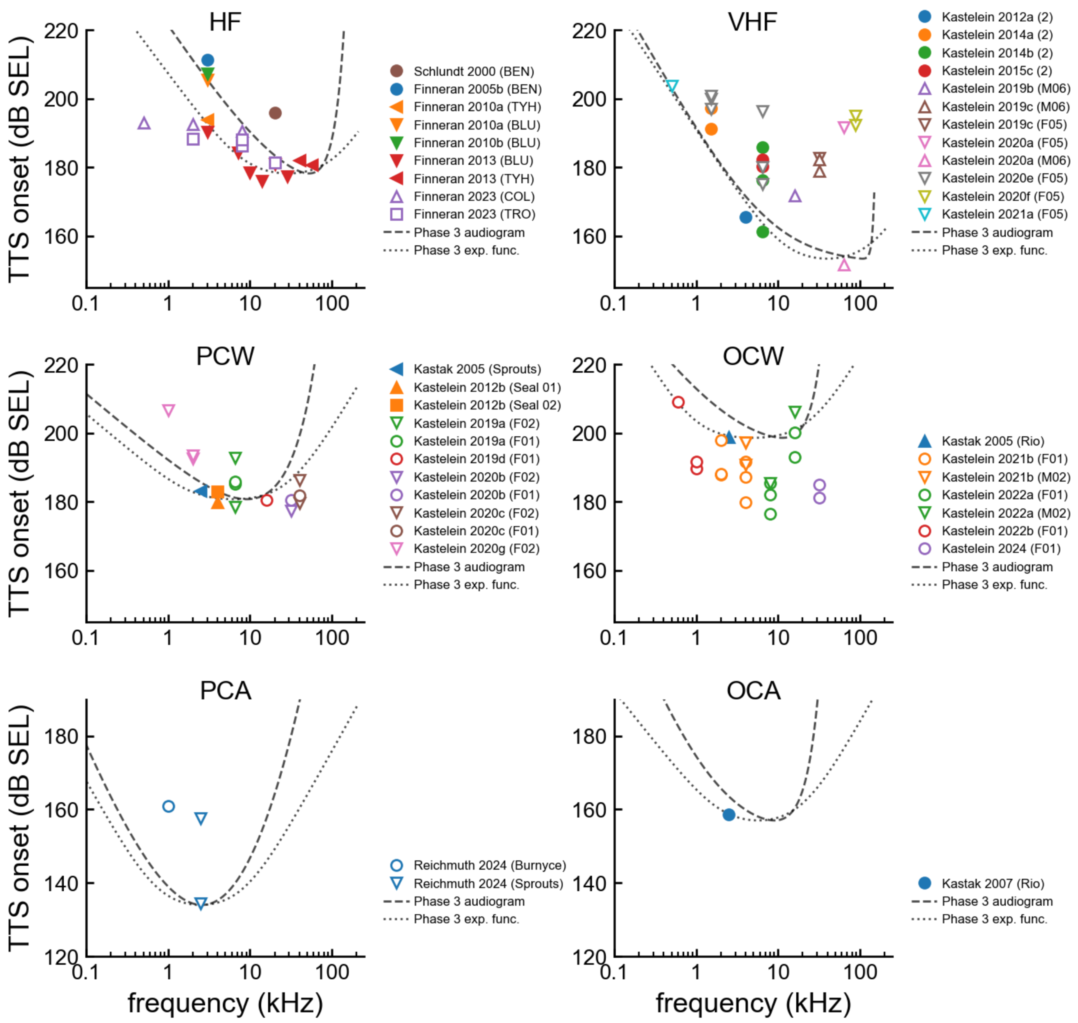
where t is the amount of TTS, L is the SEL, and m_1 and m_2 are fitting parameters. This particular function has an increasing slope when $L < m_2$ and approaches a linear relationship for $L > m_2$ (Maslen, 1981). The linear portion of the curve has a slope of $m_1/10$ and an x-intercept of m_2. Fitting was accomplished using the curve_fit function in the optimize module of the Python package SciPy (Virtanen et al., 2020).

Some TTS data do not fit the accelerating growth predicted by Eq. (6), but instead show some growth followed by a plateau, where further increases in SEL do not result in increasing TTS (referred to as asymptotic threshold shift). These datasets were visually identified and fit instead with the function

$$t(L) = \frac{T_F}{1 + 10^{p(L_0 - L)}} \tag{7}$$

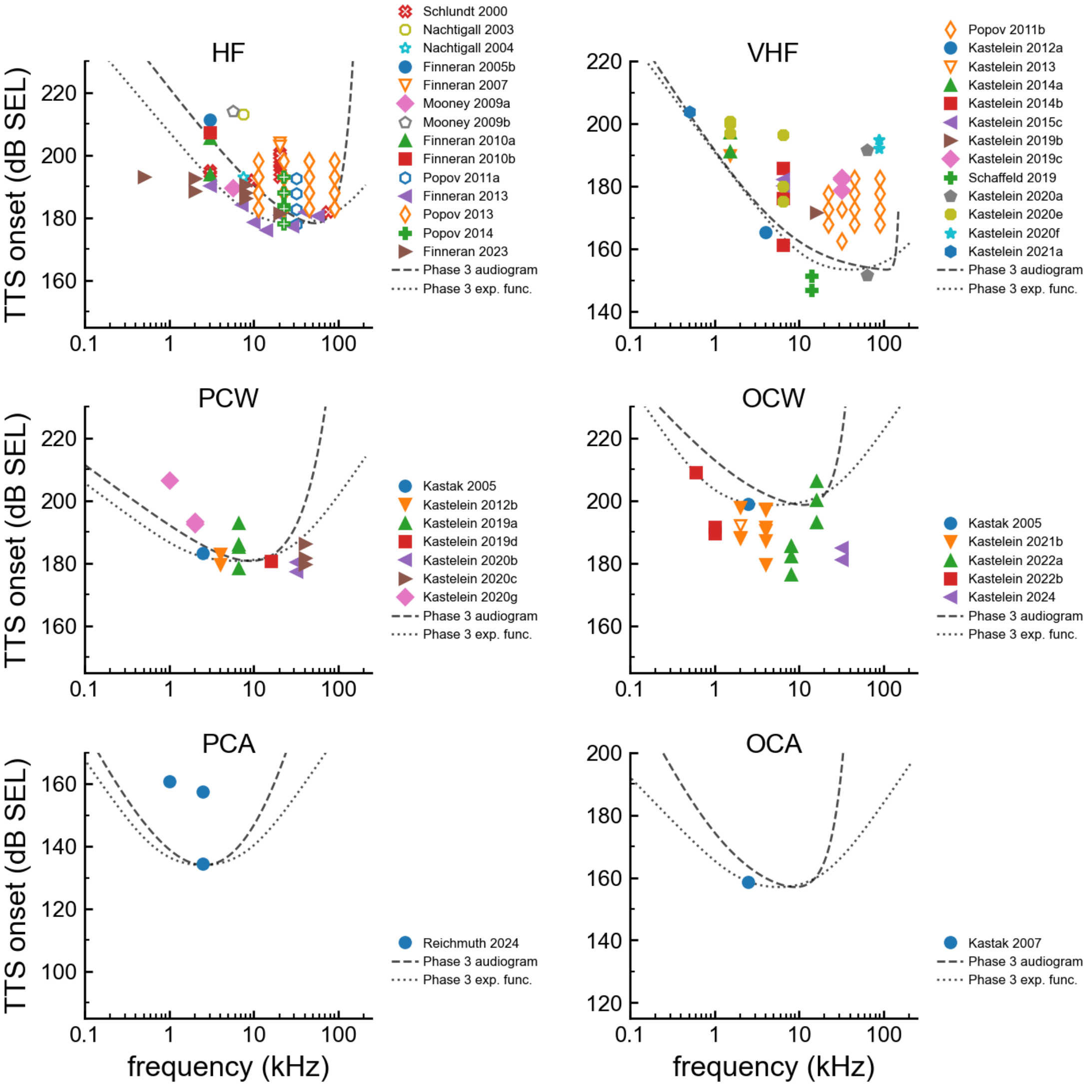
where t is the amount of TTS, L is the SEL, and T_F, p, and L_0 are fitting parameters. This function has a value of zero when $L \ll L_0$, then increases and asymptotically approaches T_F when $L > L_0$. Fitting was done with the curve fit function in the optimize module of the Python package SciPy (Virtanen et al., 2020).

After fitting Eq. (6) or (7) to the TTS growth data, the SEL necessary to induce 6 dB of TTS was determined. Extrapolation was not performed when estimating TSS onset; this means only data sets with exposures producing TTS both above and below 6 dB were used to estimate TTS onset. Figure C-1 to Figure C-5 (Appendix C) show all behavioral TTS data to which growth curves defined by Eq. (6) or (7) could be fit. The TTS onset exposure values, growth rates, and references to these data are provided in Table C-1 to Table C-5. The resulting TTS onset SELs as functions of frequency are summarized in Figure 19, with the Phase 3 composite audiograms and exposure functions for comparison. Figure 20 also shows additional data not used for TTS onset determination, either because the data were from AEP measurements, or all TTSs were > 6 dB (thus TTS onset could not be determined).



- Solid symbols indicate data that were available for Phase 3.
- Open symbols indicate new data since Phase 3 analyses.
- Dashed line: Phase 3 composite audiogram.
- Dotted line: Phase 3 exposure function.
- Units for TTS onset are dB re1 $\mu\text{Pa}^2\text{s}$ in water (groups HF, VHF, PCW, OCW) and re 20 1 $\mu\text{Pa}^2\text{s}$ in air (groups OCA, PCA).

Figure 19. SELs corresponding to TTS onset for each marine mammal species group, obtained from TTS growth functions (see Appendix C).



- Solid symbols indicate onset TTS data obtained by interpolation within TTS growth functions (Appendix C)
- open symbols indicate data with TTS ≥ 6 dB, but for which TTS onset could not be determined.
- Dashed line: Phase 3 composite audiogram.
- Dotted line: Phase 3 exposure function.
- Units for TTS onset are dB re $1\mu\text{Pa}2\ \text{s}$ in water (groups HF, VHF, PCW, OCW) and dB re $(20\mu\text{Pa})$ 2 s in air (groups OCA, PCA).

Figure 20. SELs corresponding to TTS ≥ 6 dB for each marine mammal species group.

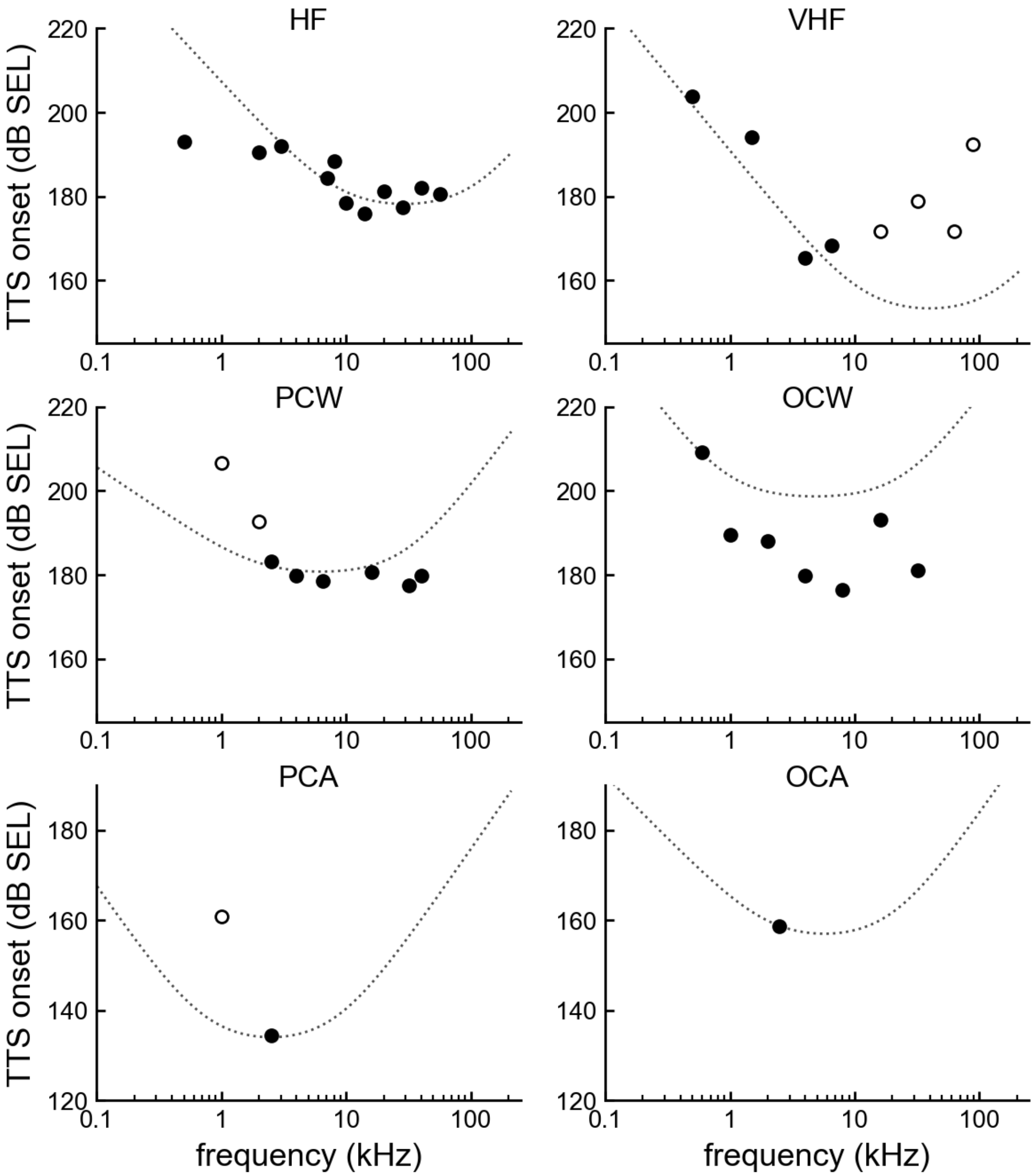
For fitting the exposure function parameters in Eq. (4), the data shown in Figure 19 were reduced to a single value at each frequency for each group (otherwise, some frequencies would exert more influence on the fitting process than others). This was accomplished by first identifying multiple data for the same animal at a single exposure frequency. This typically occurred when hearing was tested at multiple frequencies after an exposure, or exposures with different duty cycles were utilized. In these cases, only the single, lowest onset-TTS exposure level was utilized (the others were excluded from further analysis). Similarly, TTS onset data obtained from post-exposure testing at extended time periods (e.g., >5 min post-exposure) were eliminated from further analysis. The mean SEL for TTS onset was then computed at each frequency for which more than one data point existed. Figure 21 shows the resulting mean onset TTS SELs versus exposure frequency for each group.

Finally, some mean TTS onset data points for groups VHF and PCW (represented with an open circle in Figure 21) were excluded from the fitting process. This was done as a precautionary measure, where new data indicate higher TTS onset values than those predicted by Phase 3, but uncertainties in the data suggest that some caution should be exercised:

> For VHF, new data suggest substantially higher onset TTS SELs at frequencies above ~10 kHz compared to the Phase 3 predictions, with high variability in the TTS onset data for harbor porpoises at 63 kHz (~40 dB difference in TTS onset for the two porpoises). Furthermore, the harbor porpoise behavioral TTS onset SELs are significantly higher than SELs resulting in large amounts (e.g., 23–45 dB) of AEP TTS in Yangtze finless porpoise (see Figure 19). Although some differences in AEP/behavioral TTS data are expected, these large differences indicate that caution is warranted in adopting the high-frequency behavioral TTS data at the present time. For this reason, the VHS behavioral TTS onset data at frequencies > 10 kHz were not used during the exposure function fitting process.
>
> For PCW, new data below 2.5 kHz show significantly higher TTS onset compared to the Phase 3 predictions. It is surprising that the harbor seal TTS onset data at 1-2 kHz are ~10 dB higher than that of dolphins, given the better hearing sensitivity for seals at lower frequencies. The slope of the TTS data at low frequencies is also substantially higher than the audiogram slope (47 vs 33 dB/dec); this is also unexpected: the increased spread of excitation within the cochlea at the high sound levels associated with TTS would be expected to make the TTS slope shallower than the audiogram slope, not steeper. There are also uncertainties regarding the effective exposure level for the seals, since the animals spent a significant amount of time at the water's surface during the noise exposures, suggesting the animals may have behaviorally mitigated the exposure. Given these concerns and the limited nature of the data at present, harbor seal TTS onset data below 2.5 kHz were excluded from the Phase 4 fitting process.

For PCA, substantially higher TTS onset was observed in the N. elephant seal compared to the harbor seal. These data fit emerging evidence suggesting that Monachinae have lower hearing sensitivity and less susceptibility to noise compared to Phocinae, and thus TTS onset for Monachinae would be too high for Phocinae. Therefore, the N. elephant seal data were excluded from the Phase 4 fitting process.

Note that even though these data are not directly used in the fitting process, they are still considered in evaluating the final exposure function (i.e., there is no question that TTS occurred, so the mean TTS onset SELs should be above the resulting exposure function). As additional data become available, the decision whether to include these data will be re-assessed. Future studies may increase confidence in these data and thus warrant their direct inclusion in the fitting process.



- Open symbols indicate mean onset TTS data that were not used during the fitting process.
- The dotted line shows the Phase 3 exposure function.

Figure 21. Mean TTS onset SELs for each species group as a function of exposure frequency.

2.6.2 Non-Impulsive (Steady-State) Exposures–AINJ Onset

There has been one documented occurrence of PTS in a marine mammal after an intense noise exposure: Reichmuth et al. (2019) reported a PTS of 8 dB at 5.8 kHz in a harbor seal after exposure to a 4.1 kHz tone with (unweighted) SEL of 199 dB re 1 µPa^{2}s. The initial TS (1 min post-exposure) was ~57 dB. Although these data are not suitable for directly deriving AINJ thresholds, they provide an opportunity to compare the resulting AINJ threshold value to actual PTS data.

Beyond Reichmuth et al.(2019), there are no direct data relating auditory injury to noise exposure in marine mammals, thus exposures producing 40 dB TTS were used as a proxy to estimate onset AINJ. Since few marine mammal TTS studies have resulted in 40 dB of TTS, TTS growth curves were extrapolated to determine the SEL required for a TTS of 40 dB. To avoid over-estimating AINJ onset by using growth curves based on small amounts of TTS, where the growth rates are shallower than at higher amounts of TTS, extrapolation was only performed if the measured TTS exceeded 20 dB. From these growth curves, the SEL difference between TTS onset (6-dB TTS) and estimated AINJ onset (40-dB TTS) was calculated (see Figure C-1 to Figure C-5, Table C-1 to Table C-5).

2.6.3 Impulsive Exposures

Marine mammal TTS data from impulsive sources are limited to four studies with measured TTS of 6 dB or more (Table 12):

> 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).
>
> 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 (unweighted SEL 165–166 dB re 1 µPa^{2}s, peak SPL of 195 dB re 1 µPa). Note that the data from Lucke et al. (2009) are based on AEP measurements; however, they are used here because of the limited nature of the impulse TTS data for marine mammals and the likelihood that the VHF cetaceans are more susceptible than the HF cetaceans (i.e., use of the HF cetacean value is not appropriate). Based on the limited 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.
>
> Sills et al. (2020b) reported TTS of 6 dB in a bearded seal after exposure to four impulses from a seismic air gun (unweighted, single-impulse SEL of 185 dB re 1 µPa^{2}s or peak SPL of 203 dB re 1 µPa). Note that when the same individual was exposed to single impulses with the same peak SPL, no measurable mean TTS was obtained, therefore these data cannot be used to establish a peak SPL threshold.
>
> Mulsow et al. (2023) behaviorally measured TTS in three dolphins exposed to sequences of narrowband (1/6-octave), 10-ms noise bursts centered at 8 kHz (unweighted, single-impulse SEL ~160 dB re 1 µPa^{2}s or peak SPL ~183 dB re 1 µPa). Inter-pulse intervals ranged from 1.25 to 40 s, and the number of impulses varied from 40 to 2560. Maximum mean TTS was 16 dB. At the same peak SPLs, some conditions (i.e., fewer impulses) produced no TTS. Therefore, these data cannot be used to establish a peak SPL threshold.

The small, reported amounts of TTS and/or the limited distribution of exposures prevent these data from being used to estimate AINJ onset.

Several impulsive noise exposure studies have also resulted in < 6 dB (behavioral) TTS (see Table 12):

> *HF:* 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.
>
> *VHF*: Kastelein et al. (2015b) 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 (simulated impact pile driving). The exposure contained 2760 individual impulses presented at an interval of 1.3 s (total exposure time was 1 h). The average single-impulse, 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. Kastelein et al. (2016) observed behaviorally measured mean TTS up to 3 dB at 4 kHz and 5 dB at 8 kHz after harbor porpoises were exposed to up to 16560 simulated impact pile strikes. The average single-impulse, unweighted SEL was approximately 145 dB re 1 µPa^{2}s and the maximum cumulative (unweighted) SEL was approximately 187 dB re 1 µPa^{2}s. Kastelein et al. (2017c) measured mean TTS of 3–4 dB at 4 kHz after a harbor porpoise was exposed to 10–20 impulses from a pair of seismic air guns. The average single-impulse, unweighted SEL was approximately 178 dB re 1 µPa^{2}s, the maximum cumulative (unweighted) SEL was approximately 191 dB re 1 µPa^{2}s, and the maximum peak SPL was 199 dB re 1 µPa. Subsequent testing with four airguns and cumulative SELs up to 199 dB re 1 µPa^{2}s produced maximum mean TTS of 3 dB (Kastelein et al., 2020g).
>
> *OCW*: Finneran et al. (2003) exposed two sea lions to single impulses from an arc-gap transducer with no measurable TTS (maximum unweighted SEL = 163 dB re 1 µPa^{2}s, peak SPL = 203 dB re 1 µPa).
>
> *PCW*: 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^{2}s, peak SPL ~ 203 dB re 1 µPa). Kastelein et al. (2018a) exposed two harbor seals to simulated impact pile driving strikes with single-impulse, unweighted SEL ~151 dB re 1 µPa^{2}s, maximum cumulative (unweighted) SEL ~193 dB re 1 µPa^{2}s, and maximum peak SPL ~176 dB re 1 µPa. The maximum observed TTS was 4 dB.

Table 12. Summary of existing data for marine mammal TTS from impulsive sources.

Study	Group	Subject	Peak SPL (dB SPL)	Wgt. SEL (dB SEL)	Num.	Cumulative wgt SEL (dB SEL)	TTS onset, SEL	$C_s - C_i$ (dB SEL)	THS onset, peak SPL	Peak SPL dynamic range (dB SPL)
Finneran 2000	HF	BEN, MUK	217	176	1	176		-		-
Finneran 2002	HF	MUK	224	177	1	177	*	4.0	*	173
Finneran 2015	HF	BLU, TYH, OLY	210	157	10	167		-		-
Mulsow 2023	HF	OLY	183	162	40	178	*	3.0		-
Mulsow 2023	HF	TRO	183	159	40	175	*	6.0		-
Mulsow 2023	HF	TYH	183	160	640	188	*	-7.0		-
Kastelein 2015b	VHF	2	180	112	2760	146		-		-
Kastelein 2016	VHF	02, 04	-	110	16560	152		-		-
Kastelein 2017c	VHF	6	199	136	20	149		-		-
Kastelein 2020d	VHF	6	202	-	40	-		-		-
Lucke 2009	VHF	Eigil	196	144	1	144	*	17	*	147
Finneran 2003	OCW	NRT, LIB	203	157	1	157		-		-
Kastelein 2018a	PCW	01,02	176	143	16560	185		-		-
Reichmuth 2016	PCW	TUNU, AMAK, NATCHEK, NAYAK	203	158	1	158		-		-
Sills 2020b	PCW	Noatak	203	162	4	168	*	7.0		-

- SEL values are in dB re $1\mu\text{Pa}^2\text{s}$.
- Peak SPL values are in dB re $1\mu\text{Pa}$.
- Exposures with cumulative SEL associated with onset TTS are indicated by an asterisk in the "TTS onset, SEL" column.
- For these exposures, $C_s - C_i$ is the difference between the onset TTS weighted SEL threshold for non-impulsive and impulsive exposures.
- Exposures with peak SPL associated with onset TTS are indicated by an asterisk in the "TTS onset, peak SPL" column. For these exposures, "peak SPL dynamic range" indicates the difference (in dB) between the peak SPL TTS onset (in dB re $1\mu\text{Pa}$) and the hearing threshold at f_0 (in dB re $1\mu\text{Pa}$).

2.7 TTS EXPOSURE FUNCTIONS FOR SONARS

2.7.1 Overview

Derivation of the parameters for the weighting/exposure functions consisted of two main steps: First, for groups with sufficient TTS onset data, the parameters K, a, b, f_1, and f_2 were determined. Then, extrapolation procedures were used to derive the exposure function shapes for the remaining groups. The specific steps are described in the following sections.

2.7.2 Low- and High-Frequency Exponents (*a*, *b*)

As in Phase 3, 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 11). This causes the weighting function slope to match the shallower slope of the audiogram or equal latency contours at low frequencies. This approach was used instead of directly using the low-frequency slope of the TTS onset data because of the limited number of data points available for TTS onset at low frequencies compared to the audiogram data (e.g., VHF, PCW, OCW) and/or weak fits to the data (e.g., HF).

The high-frequency exponent, b, was fixed at $b = 5$, which is higher than that used in the Phase 3 functions ($b = 2$). The value was increased to better fit the OCW function without substantially affecting the other group fits.

2.7.3 Frequency Cutoffs (*f₁*, *f₂*) and Gain Parameter (*K*)

For groups HF, VHF, OCW, and PCW, nonlinear regression was used to find values of K, f_1, and f_2 to best fit Eq. (4) to the onset TTS data. Nonlinear regression was performed using the curve fit function in the optimize module of the Python package SciPy (Virtanen et al., 2020). For some datasets, Eq. (4) can exhibit high dependency among the parameters, resulting in small changes in the function despite large changes in parameter values. This can cause problems in extrapolating to the other groups. Therefore, the optimization process was constrained so that $f_L \le f_1 \le F_0$ and $F_0 \le f_2 \le f_H$, where f_L and f_H are the frequencies below and above F_0 (the composite audiogram frequency of best hearing), respectively, where the composite audiogram thresholds were 40 dB above the minimum audiogram threshold at F_0.

Following each curve-fit, the frequencies at which the resulting exposure function amplitude exceeded the minimum value by 10 dB were compared to the corresponding frequencies for the composite audiogram (see Figure 22). If the lower exposure function frequency was above the audiogram frequency, the parameter f_1 was adjusted downward until the exposure function and audiogram frequencies matched. Similarly, if the upper exposure function frequency was below the audiogram frequency, the parameter f_2 was adjusted upward until the exposure function and audiogram frequencies matched. This procedure ensured that the exposure function 10-dB bandwidth was at least as wide as the audiogram since it is expected that the high sound levels capable of causing TTS would cause the exposure function to "flatten" relative to the audiogram. The practical effect of this step was to decrease f_1 for the PCW and OCW groups and increase f_2 for the VHF group.

Figure 22 compares (a) after fitting Eq. (4) to the onset TTS data, the frequencies at which the exposure function amplitude was 10 dB above the minimum ($L_E \text{ and } U_E$) were compared to the corresponding frequencies in the composite audiogram ($L_A \text{ and } U_A$, respectively) and (b) If $L_E > L_A$, $\text{then}\, f_1$ in Eq. (4) was iteratively decreased until $\mathrm{L_E} = \mathrm{L_A}$. Similarly, if $U_E < U_A$, f_2 in Eq. (4) was iteratively increased until $U_E = U_A$.

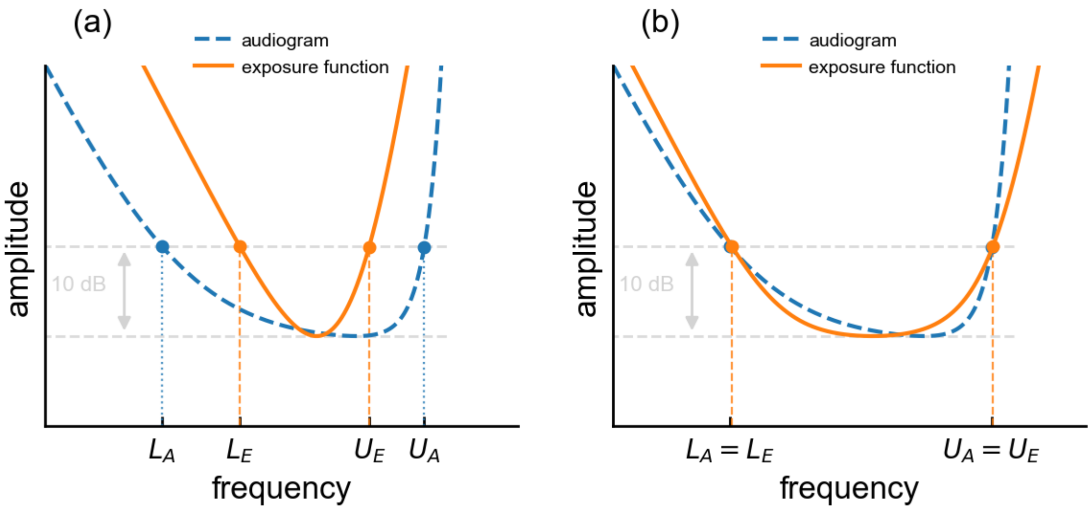


Figure 22. Audiogram and exposure function comparison and adjustment process.

To determine f_1 and f_2 for the remaining groups, the parameters ΔT_1 and ΔT_2 were defined, such that ΔT_1 was the amount that the composite audiogram threshold at f_1 exceeded the minimum threshold value, and ΔT_2 was the amount that the composite audiogram threshold at f_2 exceeded the minimum threshold value. After determining the best-fit values of f_1, f_2, and K for groups HF, VHF, OCW, and PCW, ΔT_1 and ΔT_2 were determined for each group: ΔT_1 = 36.8, 11.5, 3.9, 6.5 dB and ΔT_2 = 38.6, 22.7, 38.9, 39.4 dB, for HF, VHF, OCW, and PCW, respectively. For ΔT_1, the value at 36.8 appears to be an outlier; therefore, the median value of ΔT_1 (9.0 dB) and the mean of ΔT_2 (34.9 dB) were used in conjunction with the composite audiograms for the LF, SI, PCA, and OCA groups to determine f_1 and f_2.

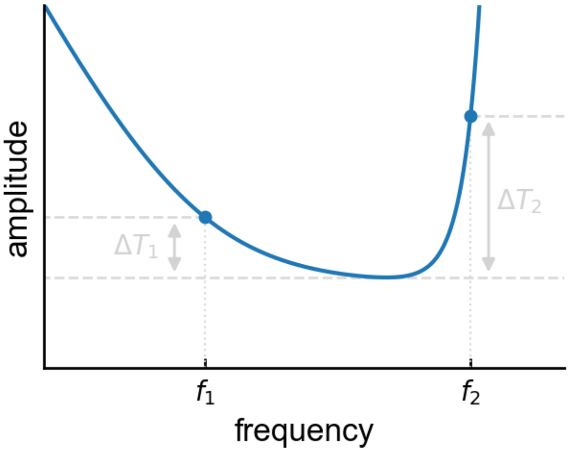


Figure 23. Defining ΔT_1 and ΔT_2.

In Figure 23, the parameter ΔT_1 was defined as the amount that the composite audiogram threshold at f_1 exceeded the minimum threshold value. Similarly, ΔT_2 was defined as the amount that the composite audiogram threshold at f_2 exceeded the minimum threshold value. Central tendencies of ΔT_1 and ΔT_2 were computed for the groups HF, VHF, OCW, and PCW. For the remaining groups, f_1 and f_2 were defined as the lower and upper frequencies where the composite audiogram was ΔT_1 and ΔT_2 dB above the minimum value.

For the groups with TTS data (PCA, OCA), the gain parameter *K* was defined to minimize the mean squared error between the exposure function and TTS data for each species group.

For the mysticetes and sirenians, for which no TTS data exist, TTS onset at the frequency of best hearing (F_0) was estimated by assuming the numeric difference between the auditory threshold (in dB SPL) at F_0 and the onset of TTS (in dB SEL) at F_0 would be similar to that for the in-water marine mammal groups. Table 13 summarizes the onset TTS and composite threshold data for the HF, VHF, OCW, and PCW groups. For these groups, the mean difference between TTS onset and composite audiogram threshold at F_0 was 121 dB. For the LF group, the hearing threshold at F_0 is 56 dB re 1 µPa, therefore, the TTS onset value at F_0 is 177 dB re 1 µPa^{2}s (Table 12). For the SI group, the lowest threshold was 59 dB re 1 µPa, making the onset TTS estimate 180 dB re 1 µPa^{2}s (Table 13). The value of *K* was then defined so the TTS exposure function matched the estimated TTS onset at F_0.

Table 13. Differences between composite audiogram threshold values (Figure 15) and TTS onset values at the frequency of best hearing (F_0).

Group	F_0 (kHz)	Threshold At F_0 (dB SPL)	TTS onset At F_0 (dB SEL)	Difference	Estimated difference	Estimated TTS onset At F_0 (dB SEL)
VLF	2.82	56	-	-	121	177
LF	5.96	56	-	-	121	177
HF	38.5	51	183	132	-	-
VHF	117	49	167	118	-	-
OCW	6.17	64	180	116	-	-
PCW	6.67	57	176	118	-	-
SI	15.6	59	-	-	121	180
OCA	9.00	11	158	147	-	-
PCA	2.73	-3.8	134	138	-	-

- The values for the mysticetes and sirenians were estimated using the mean difference (121) from the HF, VHF, OCW, and PCW groups.

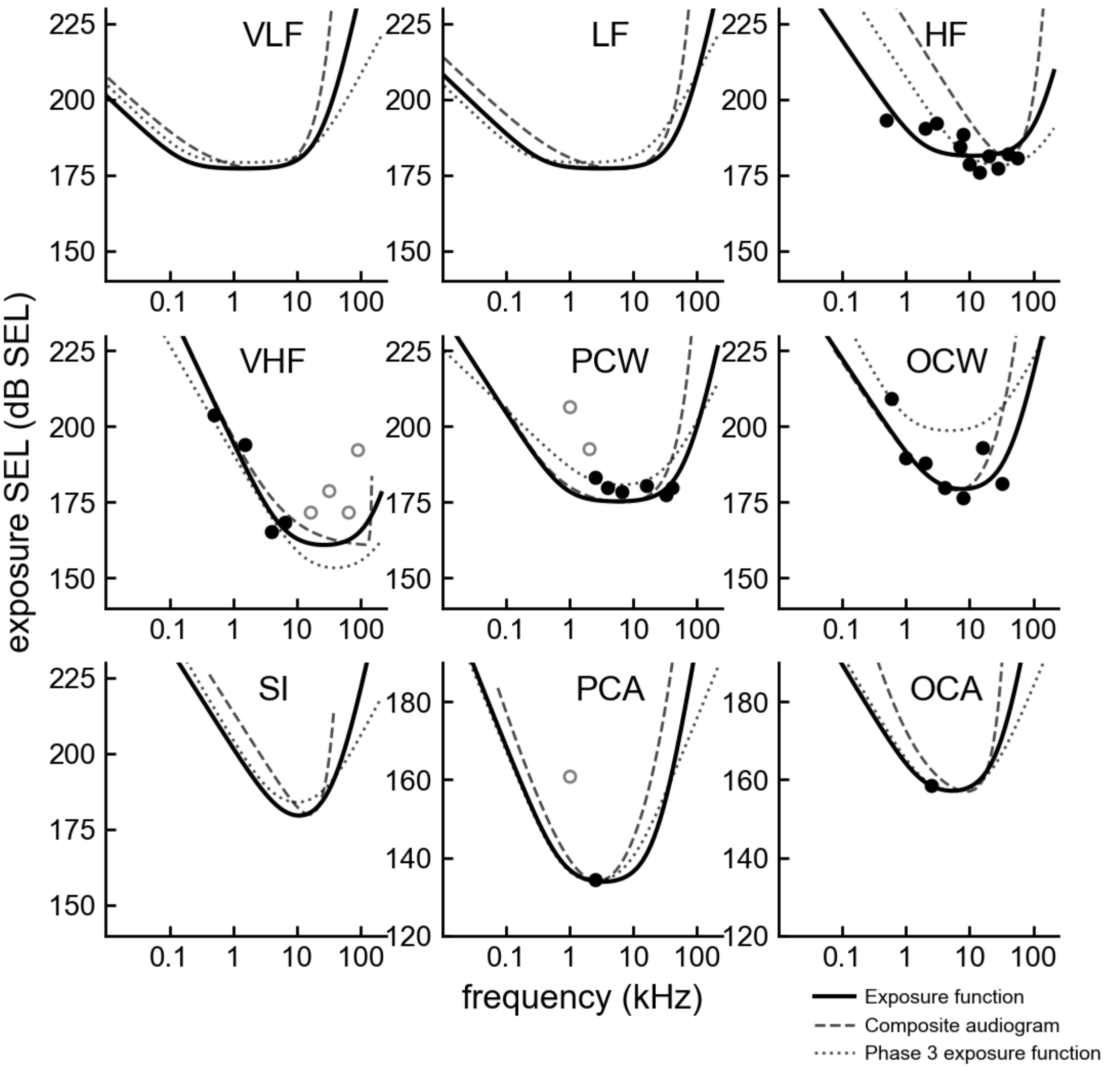
Once *K* was determined, the weighted threshold for onset TTS was determined from the minimum value of the exposure function. Finally, the constant *C* was determined by substituting parameters a, b, f_1, and f_2 into Eq. (3) and adjusting *C* so the maximum amplitude of the weighting function was 0 dB.

Table 14 summarizes the various function parameters, the weighted TTS thresholds, and the goodness of fit values between the TTS exposure functions and the mean onset TTS data. Figures 24 to 28 show the exposure functions for each group.

Table 14. Weighting function and non-impulsive TTS and AINJ exposure function parameters for use in Eqs. (3) and (4) for non-impulsive (steady-state) exposures.

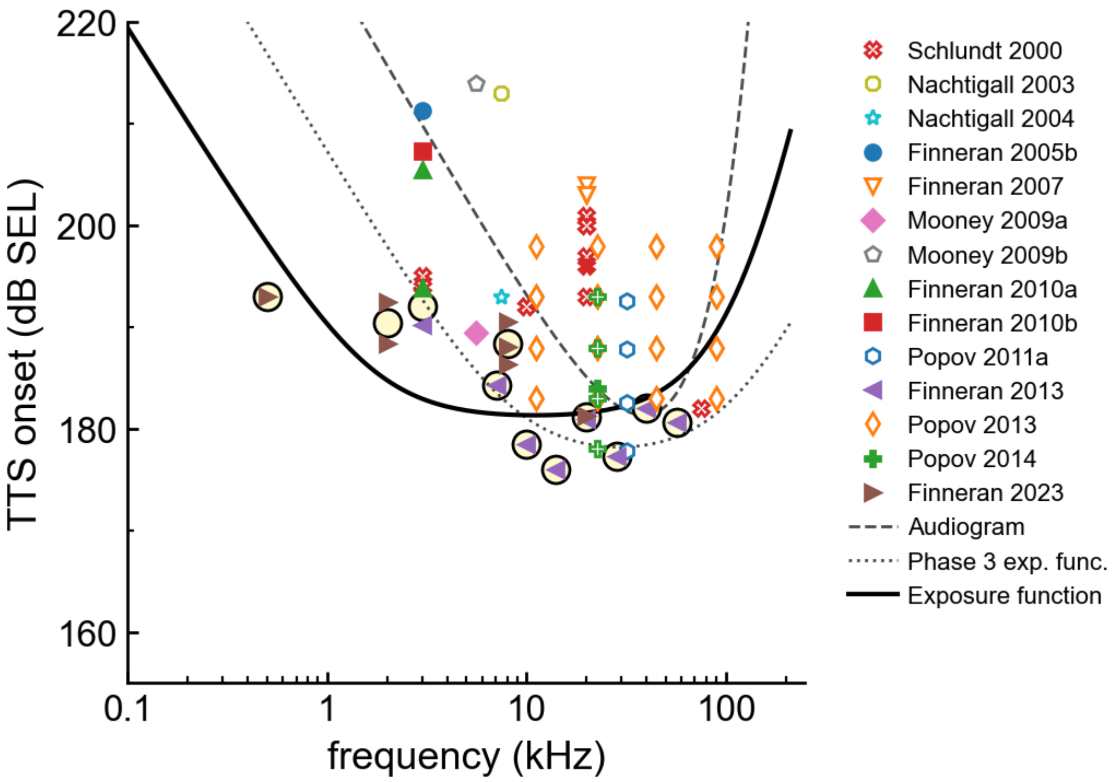
Group	a	b	f_1 (kHz)	f_2 (kHz)	C (dB)	K_{ITS} (dB)	Weighted TTS threshold (dB SEL)	K_{INJ} (dB)	Weighted INJ threshold (dB SEL)	R^2
VLF	0.990	5.00	0.168	26.6	0.120	177	177	197	197	-
LF	0.995	5.00	0.376	56.2	0.130	177	177	197	197	-
HF	1.55	5.00	1.73	129	0.320	181	181	201	201	0.247
VHF	2.23	5.00	5.93	186	0.910	160	161	180	181	0.903
OCW	1.58	5.00	2.53	43.8	1.37	178	179	198	199	0.541
PCW	1.63	5.00	0.810	68.3	0.290	175	175	195	195	- 4.69
SI	1.66	5.00	5.91	37.6	3.61	176	180	196	200	-
OCA	1.35	5.00	1.75	32.5	1.18	156	157	176	177	-
PCA	2.05	5.00	0.739	24.4	0.830	133	134	153	154	-

- R^2 values represent goodness of fit between the exposure function and the mean TTS onset data (Appendix C and Figure 24 filled symbols).



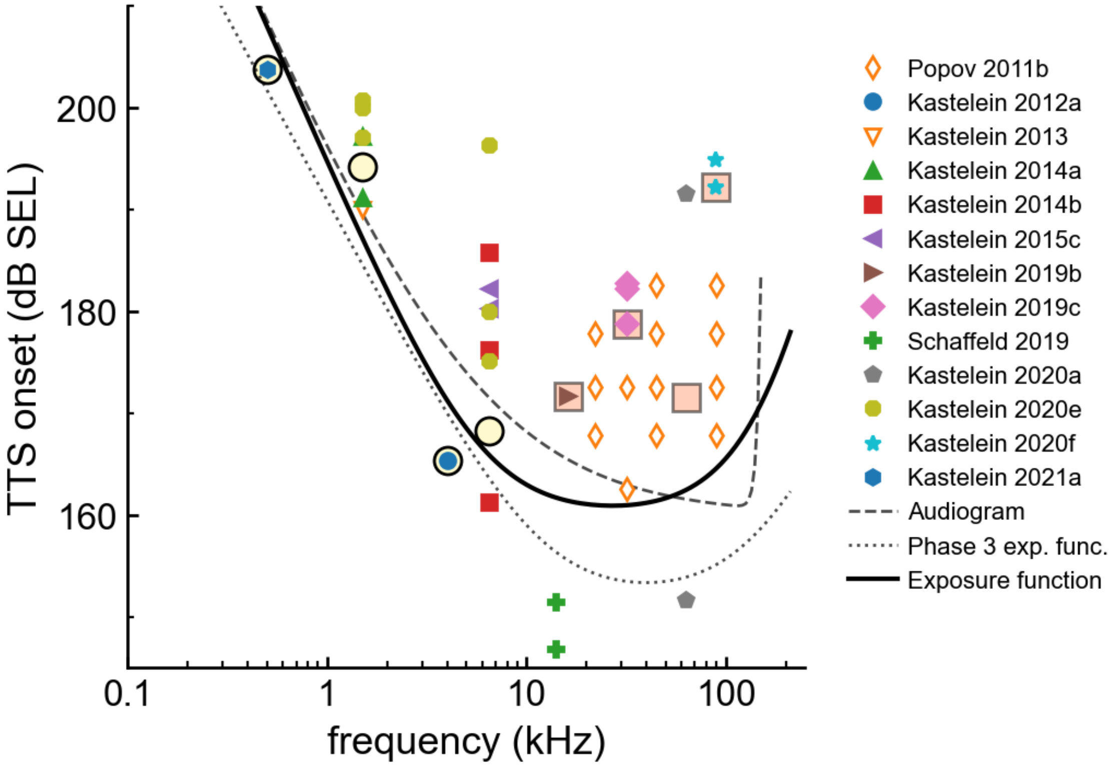
- Dashed lines - (normalized) composite audiograms. Audiograms were normalized (for display only) by adding a constant value to equate the minimum audiogram value with the exposure function minimum.
- Dotted lines: Navy Phase 3 exposure functions for TTS onset for each group.
- Filled symbols: mean onset TTS exposure data (in dB SEL) used to define exposure function shape and vertical position.
- Open symbols: mean onset TTS data not used to fit exposure functions.

Figure 24. TTS Exposure functions (solid lines) for non-impulsive exposures, generated from Eq. (4) with the parameters specified in Table 14.



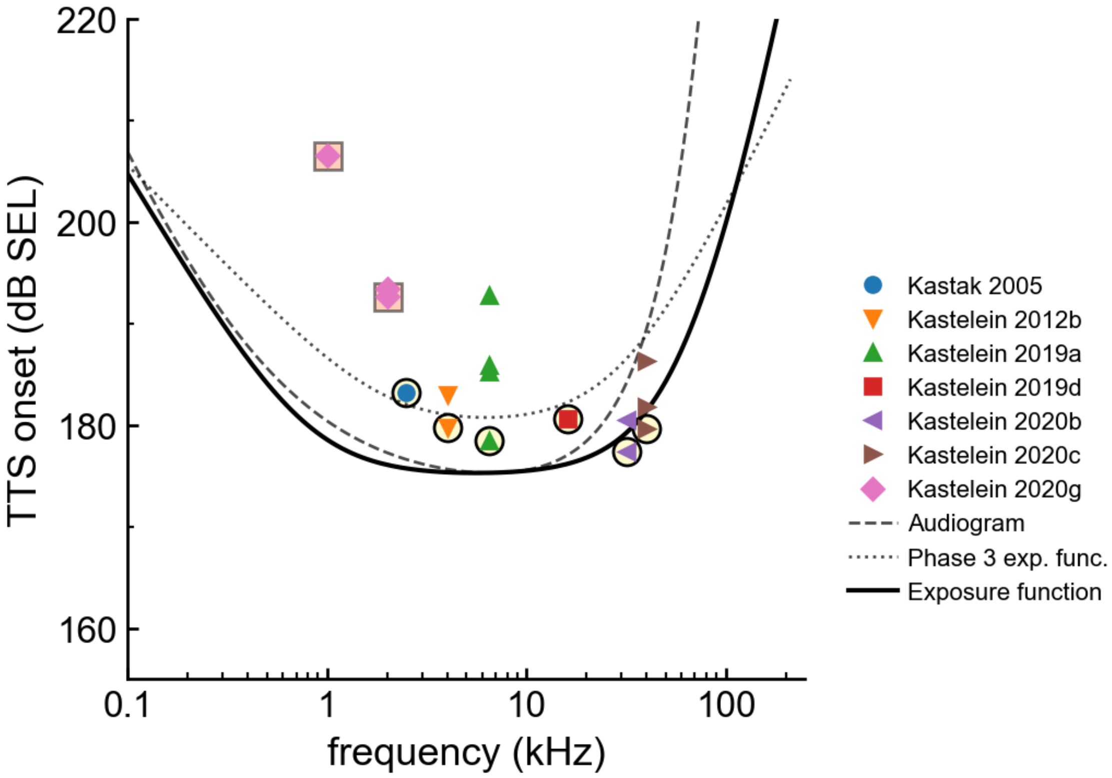
- Filled symbols: onset TTS data (Appendix C).
- Open symbols: SELs producing TTS ≥ 6 dB for which TTS onset could not be determined.
- Large, yellow-filled circles indicate (mean) TTS onset values used during the fitting process.

Figure 25. HF cetacean non-impulsive exposure function (normalized for display only), a composite audiogram, and Phase 3 exposure function compared to HF cetacean TTS data ≥ 6 dB.



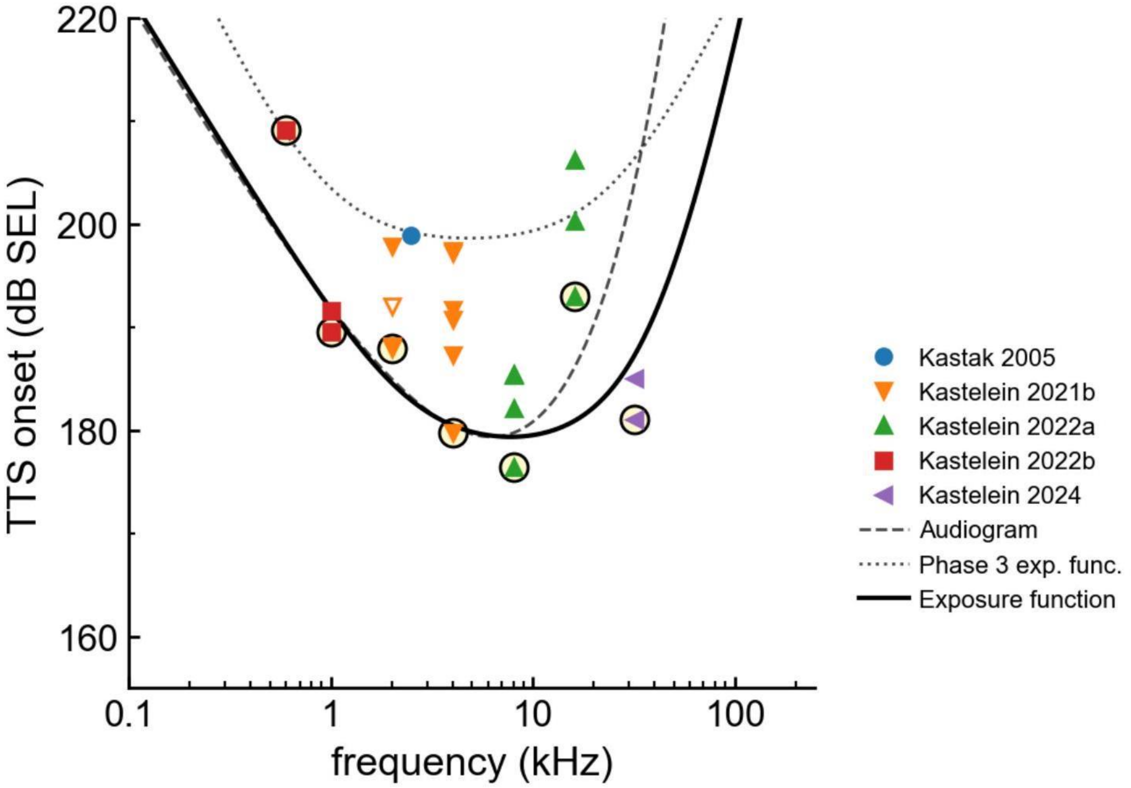
- Filled symbols: onset TTS data (Appendix C).
- Open symbols: SELs producing TTS ≥ 6 dB for which TTS onset could not be determined.
- Large, yellow-filled circles indicate (mean) TTS onset values used during the fitting process.
- Large, red-filled squares indicate (mean) TTS onset values excluded from the fitting process.

Figure 26. VHF cetacean non-impulsive exposure function, (normalized for display only) composite audiogram, and Phase 3 exposure function compared to VHF cetacean TTS data ≥ 6 dB.



- Filled symbols: onset TTS data (Appendix C).
- Large, yellow-filled circles indicate (mean) TTS onset values used during the fitting process.
- Large, red-filled squares indicate (mean) TTS onset values excluded from the fitting process.

Figure 27. PCW non-impulsive exposure function, (normalized for display only) composite audiogram, and Phase 3 exposure function compared to PCW TTS data ≥ 6 dB.



- Filled symbols: onset TTS data (Appendix C).
- Open symbol: SEL producing TTS ≥ 6 dB for which TTS onset could not be determined.
- Large, yellow-filled circles indicate (mean) TTS onset values used during the fitting process.

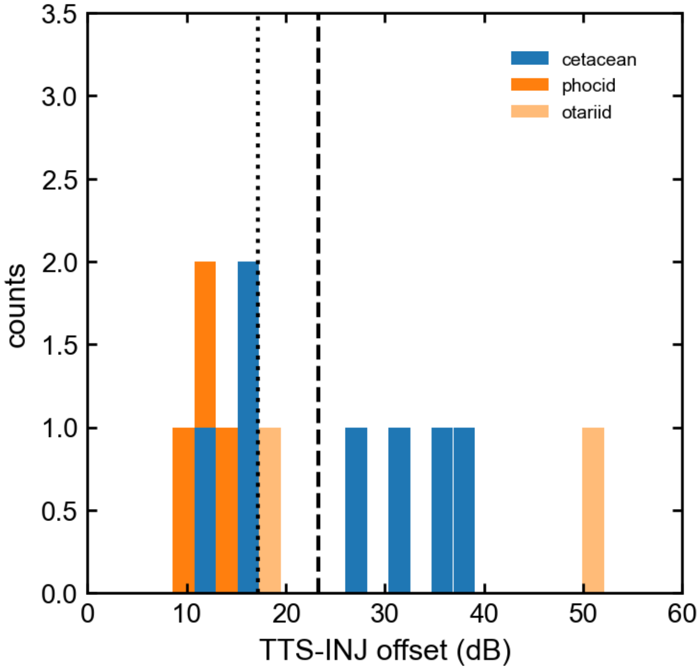
Figure 28. OCW non-impulsive cetacean exposure function, (normalized for display only) composite audiogram, and Phase 3 exposure function compared to OCW TTS data ≥ 6 dB.

2.8 INJURY EXPOSURE FUNCTIONS FOR SONARS

As in previous acoustic effects analyses (Finneran & Jenkins, 2012; Southall et al., 2007b; Southall et al., 2019a), the shape of the AINJ exposure function for each species group is assumed to be identical to the TTS exposure function for that group. Therefore, the definition of the AINJ 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 AINJ, defined here as an exposure producing 40 dB of TTS. For Navy Phase 3, a difference of 20 dB between TTS onset and AINJ onset was used for all species groups. This was based on estimates of exposure levels required for 40 dB of TTS from the marine mammal TTS growth curves.

For Phase 4, the same approach was followed, including newly published data. Table C-1 to Table C-5 reveal differences of ~9 to 52 dB (mean = 23, median = 17, *n* = 12) between TTS onset and AINJ onset (i.e., 40 dB TTS) in marine mammals. Figure 29 shows the distribution of values. For simplicity and consistency with past approaches, Phase 4 utilizes a single value of 20 dB to estimate the difference between TTS onset and AINJ onset for all species groups. The value of *K* for each AINJ exposure function and the weighted AINJ threshold were therefore determined by adding 20 dB to the *K*-value for the TTS exposure function or the TTS weighted threshold, respectively (see Table 7).

For PCW, this 20 dB difference results in an AINJ threshold of 195 dB re 1 $\mu Pa^2 s$ at 4.1 kHz. This is 4 dB below the exposure SEL of 199 dB re 1 $\mu Pa^2 s$ reported by Reichmuth et al. (2019) to result in PTS in a harbor seal. The Phase 4 PCW non-impulsive AINJ criteria are therefore consistent with the harbor seal PTS data.



- The dotted and dashed lines show the median and mean values, 17 and 23 dB, respectively.

Figure 29. Distribution of values indicating the increase in noise exposure between the onset of TTS and the onset AINJ, based on marine mammal TTS growth curves with measured TTS ≥ 20 dB (Appendix C).

2.9 TTS/AINJ EXPOSURE FUNCTIONS FOR EXPLOSIVES

The shapes of the TTS and AINJ 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 AINJ functions only requires the values for the constant *K* to be determined.

Phase 4 analyses for TTS and AINJ from underwater detonations and other impulsive sources follow previous approaches, where a weighted SEL threshold is used in conjunction with an unweighted peak SPL threshold (U.S. Department of the Navy, 2017; Finneran & Jenkins, 2012; National Marine Fisheries Service, 2016a, 2018; Southall et al., 2007b; Southall et al., 2019a). The threshold producing the greater range for effect is used for estimating the effects of the noise exposure.

Peak SPL thresholds for TTS were based on TTS data from single impulsive sound exposures that produced 6 dB or more TTS for the HF and VHF groups (the only groups for which data are available). The peak SPL thresholds from these data were 224 and 196 dB re 1 µPa, for groups HF and VHF, respectively (Table 12, Finneran et al., 2002; Lucke et al., 2009). Note the data from Sills et al. (2020b) and Mulsow et al. (2023) were not used to establish a peak SPL threshold for PCW and HF, respectively, since exposures with the same peak SPL did not always result in TTS when the number of impulses was reduced.

SEL thresholds for TTS were based on TTS data from single or multiple impulsive sound exposures that produced 6 dB or more TTS for the HF, VHF, and PCW groups (the only groups for which data are available). The SEL-based thresholds were determined by applying the Phase 4 weighting functions for the appropriate species groups to the exposure 1/3-octave frequency spectra that produced TTS, then calculating the resulting cumulative weighted SELs. When this method is applied to the exposure data from Lucke et al. (2009) and Sills et al. (2020b), the cumulative weighted SEL TTS thresholds are 144 and 168 dB re 1 µPa^{2}s, respectively (Table 12). For the HF group, cumulative weighted SELs for onset TTS were 175, 177, 178, and 188 dB re 1 µPa^{2}s (mean = 180, median = 178). Since the 188-dB value appears to be an outlier from the other three values, the median of 178 dB re 1 µPa^{2}s was therefore used as the SEL-based onset TTS for the HF group. Similarly, the median value for C_s - C_i (3.5 dB) was used for the HF group.

For species groups for which no impulse TTS data exist for TTS onset, 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 (HF, VHF, PCW):

$$G_s - G_i = \overline{C_s - C_i} \tag{8}$$

Where *G* indicates thresholds for a species group for which impulse TTS data are not available, C indicates the threshold for the groups for which data exist, the subscript s indicates a steady-state threshold, the subscript i indicates an impulse threshold, and the overbar symbol (-) indicates the mean value. For groups HF, VHF, PCW, $C_s - C_i = 3.5, 17,$ and 7.0 dB, respectively (mean $= 9.2$ dB). Therefore, for each of the remaining groups the SEL-based impulse TTS threshold is 9.2 dB below the steady-state (non-impulse) TTS threshold (Table 16).

Table 15. Summary of function parameters for use in Eqs. (3) and (4) to generate Phase 4 weighting functions and exposure functions, respectively.

Group	a	b	f_1 (kHz)	f_2 (kHz)	C (dB)	Non-impulse K_{TTs} (dB)	Non-impulse K_{INJ} (dB)	Impulse K_{THs} (dB)	Impulse $K_{[N]}$ (dB)
VLF	0.990	5.00	0.168	26.6	0.120	177	197	168	183
LF	0.995	5.00	0.376	56.2	0.130	177	197	168	183
HF	1.55	5.00	1.73	129	0.320	181	201	177	192
VHF	2.23	5.00	5.93	186	0.910	160	180	143	158
OCW	1.58	5.00	2.53	43.8	1.37	178	198	168	183
PCW	1.63	5.00	0.810	68.3	0.290	175	195	168	183
SI	1.66	5.00	5.91	37.6	3.61	176	196	167	182
OCA	1.35	5.00	1.75	32.5	1.18	156	176	147	162
PCA	2.05	5.00	0.739	24.4	0.830	133	153	124	139

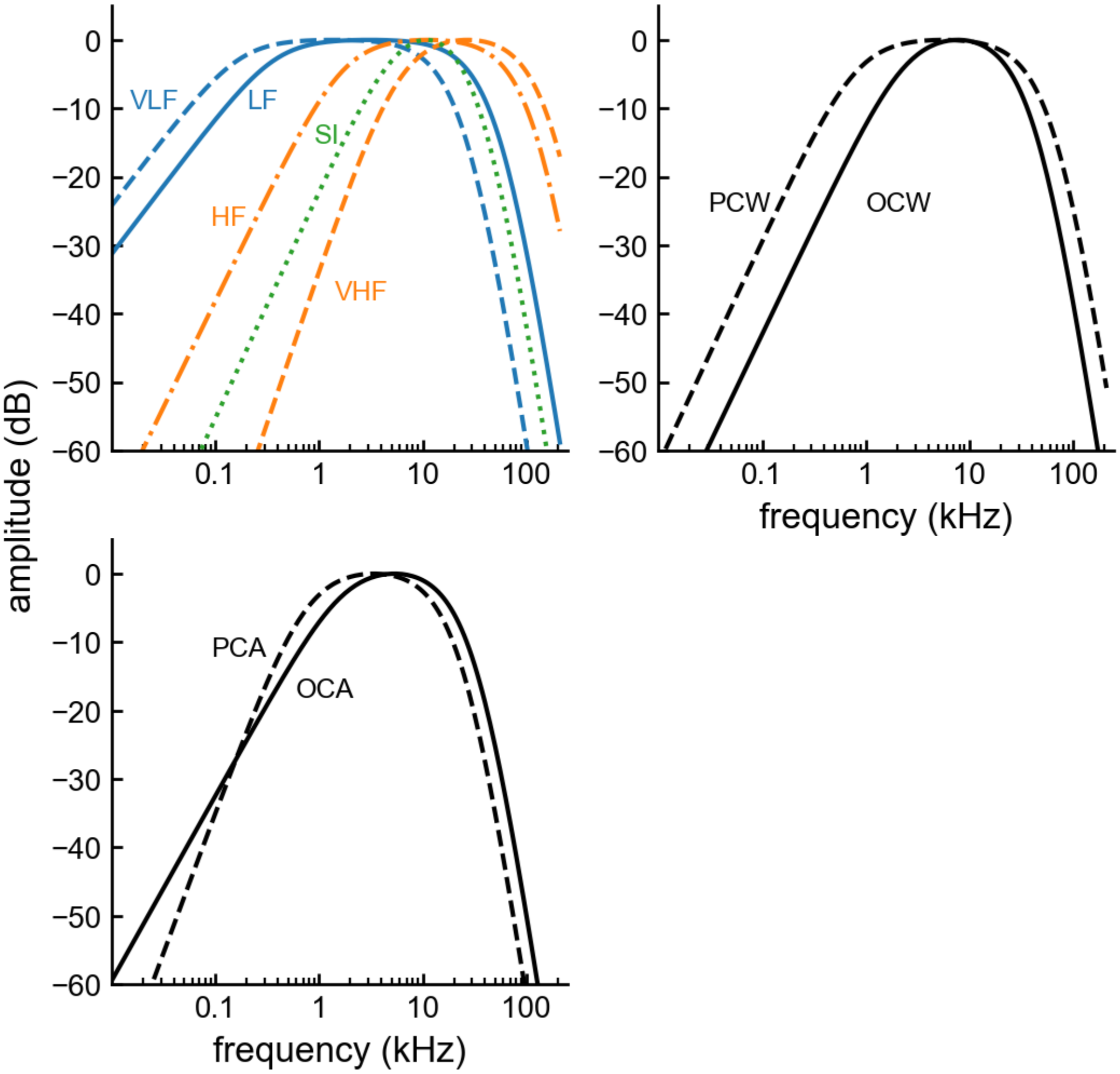
Values for K are rounded to the nearest dB.

To estimate peak SPL-based thresholds, the peak SPL "dynamic range" was defined as the difference (in dB) between the impulsive noise, peak SPL TTS onset (in dB re $1\mu\mathrm{Pa}$) and the hearing threshold at f_0 (in dB re $1\mu\mathrm{Pa}$) for the groups for which peak SPL TTS onset data are available (HF, VHF). For groups HF and VHF, dynamic ranges are 173 and 147 dB, respectively (mean, median = 160 dB). Therefore, for the remaining species groups, the impulsive peak SPL-based TTS thresholds were estimated by adding 160 dB to the hearing threshold at f_0 (Table 13).

Since marine mammal PTS/auditory injury data from impulsive noise exposures do not exist, onset-AINJ levels 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. (2007b) from impulse noise TTS growth rates in chinchillas, and utilized in subsequent analyses (U.S. Department of the Navy, 2017; Finneran & Jenkins, 2012; National Marine Fisheries Service, 2016a, 2018; Southall et al., 2019a). The appropriate frequency weighting function for each functional hearing group is applied only when using the SEL-based thresholds to predict AINJ.

Figure 30 illustrates the shapes of the various Phase 4 auditory weighting functions. Table 15 summarizes the parameters necessary to calculate the weighting function and exposure function amplitudes. Table 16 summarizes the weighted TTS and AINJ thresholds.

To properly compare the TTS/AINJ criteria and thresholds used by Navy for Phase 3 and Phase 4, both the weighting function shape and weighted threshold values must be considered; the weighted thresholds by themselves only indicate the TTS/AINJ 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/AINJ thresholds for Phase 3 and 4 (Figure 31 and Figure 32).



- Parameters required to generate the functions are provided in Table 15.

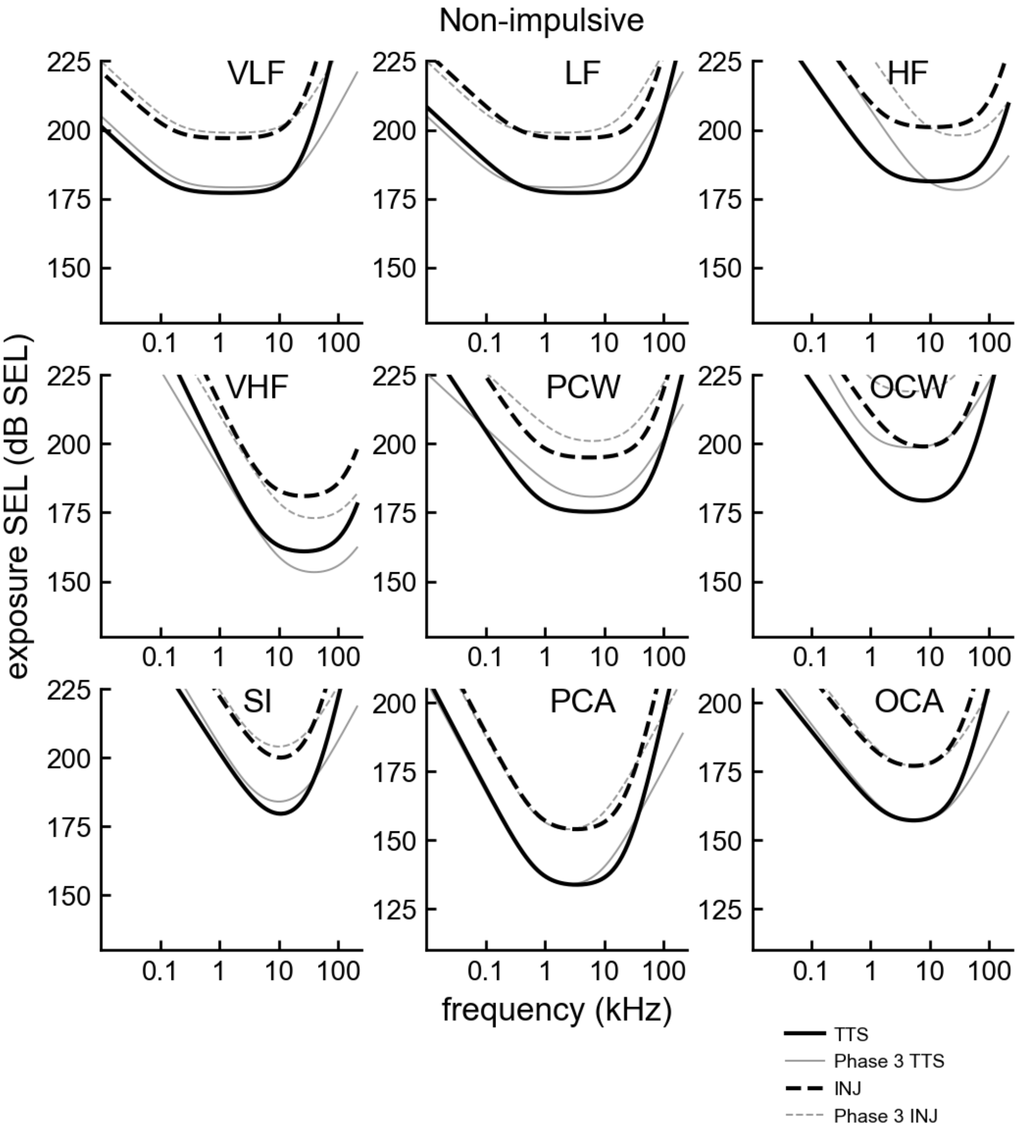
Figure 30. Navy Phase 4 weighting functions for all marine mammal species groups.

Table 16. TTS and AINJ thresholds for impulsive and non-impulsive sources.

Group	Non-impulsive TTS threshold SEL (weighted)	Non-impulsive INJ threshold SEL (weighted)	Impulsive TTS threshold SEL (weighted)	Impulsive TTS threshold peak SPL (unweighted)	Impulsive INJ threshold SEL (weighted)	Impulsive INJ threshold peak SPL (unweighted)
VLF	177	197	168	216	183	222
LF	177	197	168	216	183	222
HF	181	201	178	224	193	230
VHF	161	181	144	196	159	202
OCW	179	199	170	224	185	230
PCW	175	195	168	217	183	223
SI	180	200	171	219	186	225
OCA	157	177	148	171	163	177
PCA	134	154	125	156	140	162

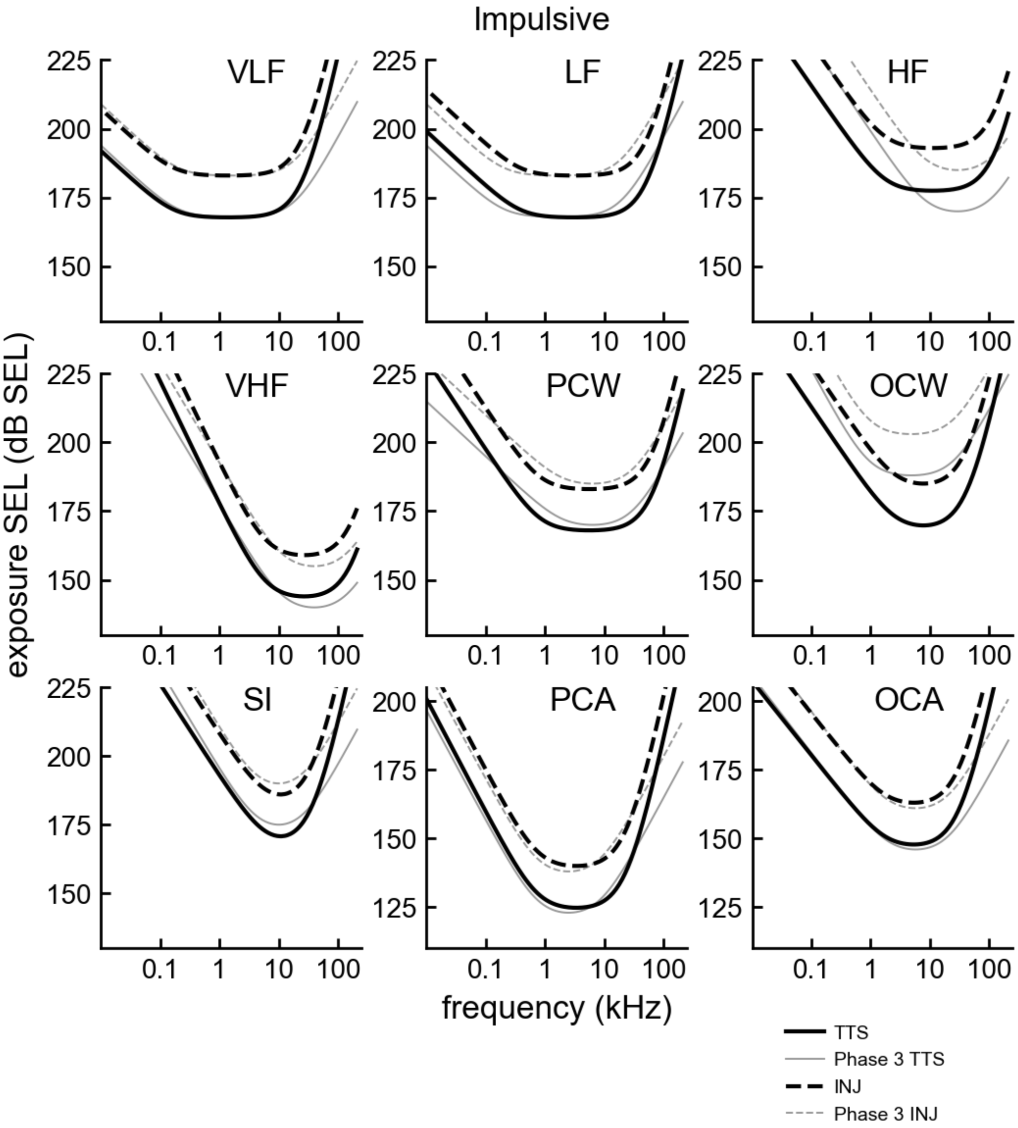
SEL thresholds in dB re $1\ \mu\text{Pa}^2\text{s}$ underwater and dB re $(20\ \mu\text{Pa})^2 s$ in air (groups OCA and PCA only).

Peak SPL thresholds in dB re $1\ \mu\text{Pa}$ underwater and dB re $20\ \mu\text{Pa}$ in air (groups OCA and PCA only).



- See Table 15 for function parameters.
- Heavy solid lines: Navy Phase 4 TTS exposure functions.
- Thin solid lines: Navy Phase 3 TTS exposure functions.
- Thick dashed lines: Navy Phase 4 AINJ exposure functions.
- Thin dashed lines: Navy Phase 3 AINJ exposure functions.

Figure 31. TTS and AINJ exposure functions for sonars and other (non-impulsive) active acoustic sources.



- See Table 15 for function parameters.
- Heavy solid lines: Navy Phase 4 TTS exposure functions.
- Thin solid lines: Navy Phase 3 TTS exposure functions.
- Thick dashed lines: Navy Phase 4 AINJ exposure functions.
- Thin dashed lines: Navy Phase 3 AINJ exposure functions.

Figure 32. TTS and AINJ exposure functions for explosives, impact pile driving, air guns, and other impulsive sources.

3 MARINE MAMMAL BEHAVIORAL RESPONSE CRITERIA

3.1 SONAR AND SONAR-LIKE SIGNALS

3.1.1 Introduction

This section outlines the criteria and thresholds used in Navy Phase 4 analyses to predict behavioral effects on marine mammals from sonar and sonar-like signals. Multiple behavioral studies provide data on how some species of marine mammals react to activities utilizing sonar and similar sound sources. Multi-year research efforts in the United States and Europe have conducted sonar exposure studies in the field with wild odontocetes and mysticetes (e.g., Southall et al. 2019b; Curé et al. 2021; Isojunno et al. 2021; Durban et al. 2022). Studies with captive animals have provided data under controlled circumstances for odontocetes and pinnipeds (e.g., Kastelein et al. 2006b, 2008, 2013d, 2019e; Houser 2013a, 2013b). Jacobson et al. (2022) published a beaked whale dose-response curve based on passive acoustic monitoring of beaked whales during U.S. Navy training activity at the Pacific Missile Range Facility (PMRF) during actual Anti-Submarine Warfare (ASW) exercises. New for Phase 4 is the inclusion of harbor porpoises with the beaked whales, based on behavioral response studies conducted on captive animals (e.g., Kastelein et al. 2000; 2019e), to create a sensitive species response function. All these data were used in developing the Navy's Phase 4 behavioral response functions.

Under the Marine Mammal Protection Act, for military readiness activities, such as Navy training and testing, behavioral 'harassment' is: "any act that disturbs or is likely to disturb a marine mammal or marine mammal stock in the wild by causing disruption of natural behavioral patterns, including, but not limited to, migration, surfacing, nursing, breeding, feeding, or sheltering, to a point where such behavioral patterns are abandoned or significantly altered." (Section 315(f) of Public Law 107-314; 16 U.S.C. 703 note).

3.1.2 Significant Behavioral Responses

In this report, the terms "significant response" or "significant behavioral response" are used in describing behavioral observations from field or captive animal research that may rise to the level of "harassment" under the MMPA for military readiness activities. Due to the nature of behavioral response research to date, in many cases, it is not possible to ascertain if observed reactions would lead to an abandonment or significant alteration of natural behavior patterns.

Behavioral response severity is described herein as low, moderate, or high. These categories are derived from the Southall et al. (2021) severity scale. This updated severity scale breaks out behavioral responses by changes that may affect survival, feeding, and reproduction.

In wild populations, low severity responses are within an animal's range of typical (baseline) behaviors and are unlikely to disrupt an individual to a point where natural behavior patterns are significantly altered or abandoned. Low severity responses include:

- Orientation response
- Startle response
- Listening
- Increase in contact calls
- Detectable changes in resting, foraging, or courtship behavior
- Change in behavior from foraging, resting, or courtship to another behavior

Moderate severity responses could become significant if sustained over a longer duration. What constitutes a long-duration response is different for each situation and species, although it is likely dependent upon the magnitude of the response and species characteristics such as body size, feeding strategy, and behavioral state at the time of the exposure.

Moderate severity responses include:

- Prolonged silencing or changes in vocal rates or signal characteristics
- Increased interval between surfacing bouts
- More directed heading
- Detectable elevation in energy expenditure or exceeding nominal baseline
- Change in behavioral state (from feeding, courtship) longer than typical
- Onset of or sustained avoidance behavior
- Defensive or aggressive social behaviors
- Increase in mother-offspring cohesion, detectable change in nursing behavior, or disruption of parental attendance
- Reduction in foraging success exceeding typical daily intake requirement
- Reduction in advertisement/courtship behavior potentially sufficient to reduce reproductive success

Moderate severity responses would not be considered significant behavioral responses if they lasted for a short duration and the animal immediately returned to their pre-response behavior. Moderate severity responses would be considered significant behavioral responses if they were sustained for a long duration (Figure 33). For the derivation of behavioral criteria in this report, a long duration was defined as a response that lasted for the duration of exposure or longer, regardless of how long that exposure lasted. This assumption was made because an examination of behavioral response data suggests that the behavioral responses would have continued had the exposure continued.

High severity responses are those with possible immediate consequences to growth, survival, or reproduction:

- Severe/sustained avoidance or displacement to area of increased predation risk
- Prolonged separation of females and dependent offspring
- Disruption of feeding or reproductive behavior sufficient to compromise health or reproductive success
- Disruption of group social structure
- Panic or flight
- Stranding

High severity responses include those with immediate consequences (e.g., stranding) and those affecting animals in vulnerable life stages (i.e., calf, pup, or cub), and are therefore always considered to be a significant behavioral reaction.

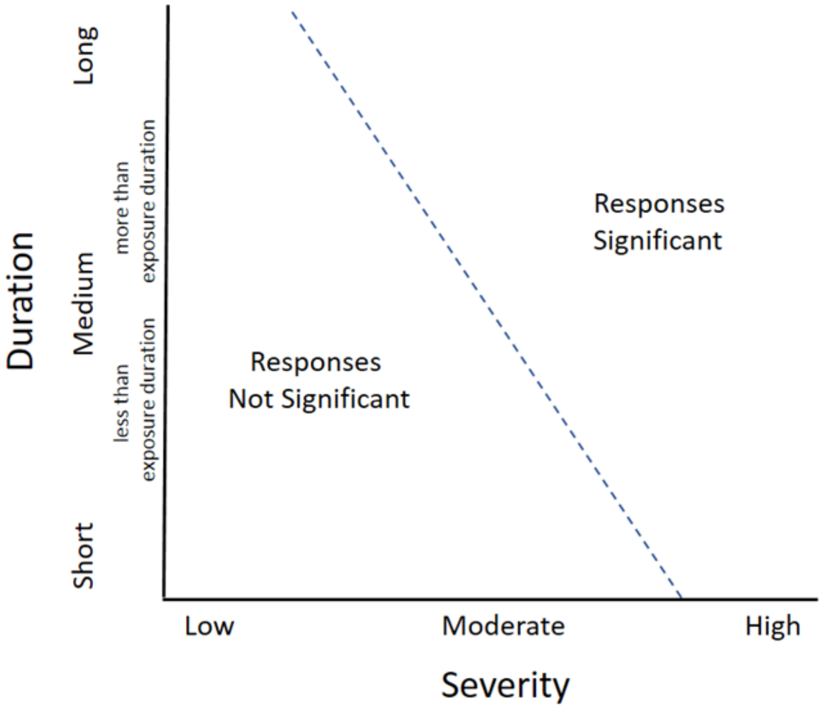


Figure 33. Determination of a Response Being Significant Based on the Duration and Severity of Behavioral Reactions

Several behavioral experiments have been conducted with animals under human care to estimate received sound levels that lead to disturbance of either normal or trained behaviors. Equating behavioral responses of animals under human care to those in the wild is inherently difficult as the context of the experiment, history of behavioral conditioning, and the nature of the environment cannot be easily equated to natural settings, nor can it be easily determined if these conditions make animals sensitive to noise exposure. Nevertheless, studies with captive animals provide greater control over the sound exposure level and greater opportunity for observation. Southall et al. (2021) separated the behavioral response severity scales of captive animals from those of wild animals to assign similar severity ranks based on the behavioral response unique to each type of study. In addition, Southall et al. (2021) separated untrained from trained responses for better clarity in identifying behavioral responses and reduced the response levels from nine to four (with the first level being no response). General examples of low severity behavioral responses in captive animals include:

- Short-term changes in orientation or short-distance avoidance of sound source
- Initial changes in task performance
- Isolated defensive behaviors

General examples of moderate to high severity behavioral responses in captive animals include:

- Aversion and frequent defensive behaviors
- Still motivated by food reward but may "game" the system to avoid sound source
- Aggression or exclusion of other individuals
- Changes in response to trained behaviors interfering with task
- Prolonged avoidance of station or exposure location
- Refusal to perform conditioned tasks

- Retreating to refuge space or logging at bottom of pool

3.1.3 Review of Phase 2 and Phase 3 Behavioral Criteria

In Navy acoustic impact analyses during Phase 2, the likelihood of behavioral effects to marine mammals from sonar and sonar-like signals was based on a probabilistic function (termed a behavioral response function [BRF]), that related the likelihood (i.e., probability) of a behavioral response to the received sound pressure level (SPL). The BRF was used to estimate the percentage of an exposed population that is likely to exhibit altered behaviors at a given received SPL, which is equivalent to the probability of response of an individual animal. This BRF relied on the assumption that sound poses a negligible risk to marine mammals if they are exposed to SPL below a certain "basement" value. Above the basement exposure SPL, the probability of a response increased with increasing SPL.

Two BRFs were used in Navy acoustic impact analyses for Phase 2: BRF1 for mysticetes and BRF2 for other species (Figure 34). The BRFs were based on three sources of data: behavioral observations during TTS experiments conducted at the U.S. Navy Marine Mammal Program (Finneran & Schlundt, 2004); reconstruction of sound fields produced by the USS Shoup associated with the behavioral responses of killer whales observed in Haro Strait (Fromm, 2009; U.S. Department of the Navy, 2003); and observations of the behavioral response of North Atlantic right whales exposed to alert stimuli containing mid-frequency components (Nowacek et al., 2004).

BRFs were not used for harbor porpoises and beaked whales during Phase 2 analyses. Instead, a step function at an SPL of 120 dB re 1 µPa was used for harbor porpoises as a threshold to predict behavioral disturbance. Threshold levels at which both captive (Kastelein et al., 2000; Kastelein et al., 2006a) and wild harbor porpoises (Johnston, 2002) responded to sound (e.g., acoustic harassment devices, acoustic deterrent devices, or other non-impulsive sound sources) were very low, ranging between 100 and 145 dB re 1 µPa. Similarly, the Navy adopted a 140 dB re 1 µPa SPL threshold for behavioral effects for all beaked whales (family: Ziphiidae) based on limited data from the instrumented Atlantic Undersea Test and Evaluation Center range in the Bahamas (McCarthy et al., 2011; Tyack et al., 2011).

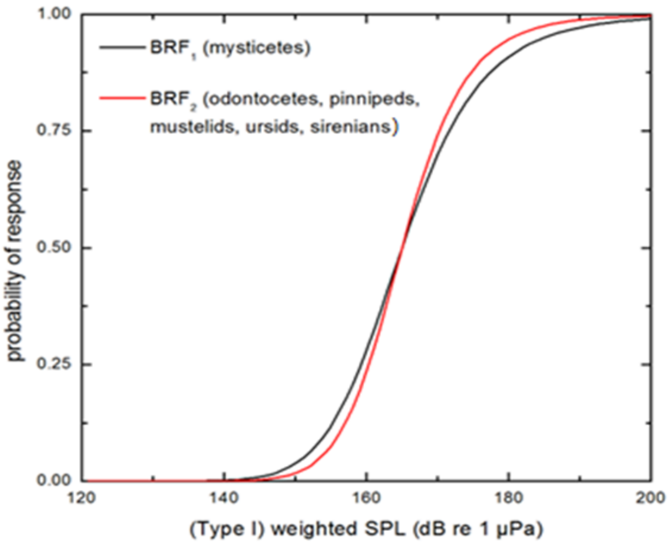


Figure 34. Phase 2 Navy Behavioral Response Functions.

In Phase 3, more data from controlled exposure experiments (CEE) and Behavioral Response Studies (BRS) were available, along with data from studies with captive animals exposed to sonar-like sounds. Only data that met the following two criteria were utilized in the Phase 3 BRFs:

- Observations of individual/group animal behavior were related to measured received levels.
- Studies were primarily designed to observe behavioral changes during controlled exposures or actual Navy activities (i.e., monitoring).

In addition, biphasic risk functions were adopted in Phase 3, rather than the monophasic functions used in Phase 2, to attempt to capture responses that were both context-driven and received level-driven (Figure 35). A hierarchical Bayesian framework was applied in the development of the BRFs, which allowed for variation in thresholds both among and between animals (for animals that had been exposed more than once) to be incorporated into the model (e.g., Miller et al. 2014). Finally, cut-off distances were applied to the data with the assumption that even significant context-based responses would not occur beyond those distances.

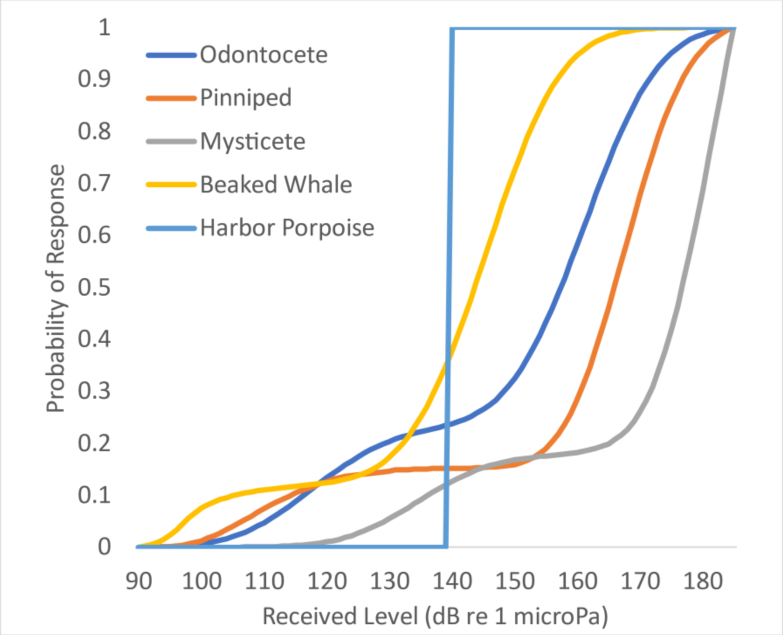


Figure 35. Phase 3 Behavioral Response Functions.

3.1.4 Dose and Contextual Responses

The received level of sound may not always be the best predictor of a marine mammal's behavioral reaction to a sound exposure. The context, including the animal's behavioral state, animal's previous experience with the sound, sound source speed and heading (either toward or away), and sound source distance, can all affect an animal's reaction (Southall, 2007; Wartzok, 2003). Ellison et al. (2011) proposed dividing behavioral reactions into level-based responses and context-based responses (Figure 36). At higher amplitudes, a level-based response relates the received sound level to the probability of a behavioral response, probably caused by auditory masking or annoyance (Ellison et al., 2011). At lower amplitudes, sound can cue the presence, proximity, and approach of a sound source and stimulate a context-based response based on factors other than received sound level (e.g., the animal's previous experience, sound source-animal separation distance, behavioral state [e.g., feeding, traveling]).

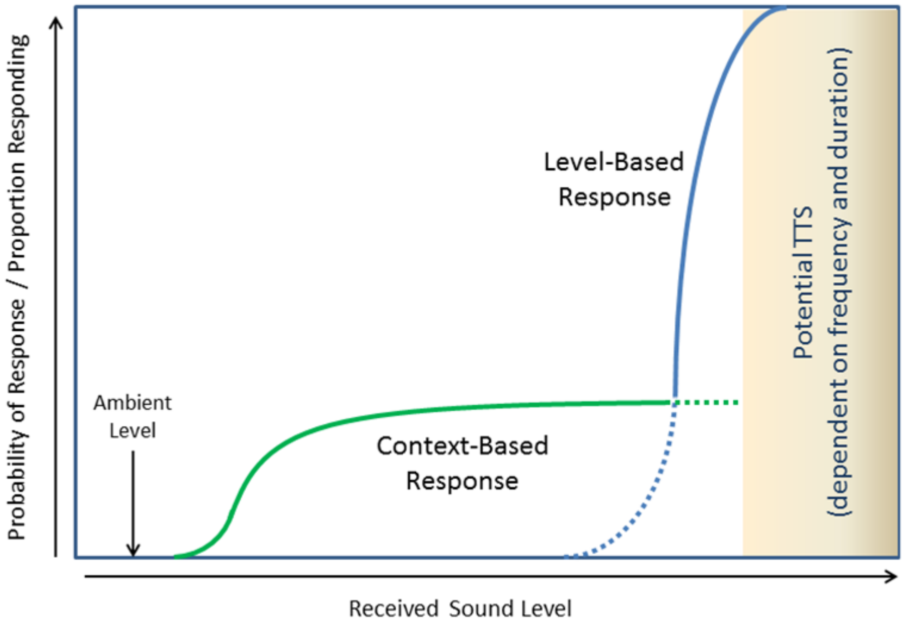


Figure 36. Conceptual framework for dividing behavioral responses due to acoustic disturbance into context-based and level-based responses (Ellison et al., 2011).

The currently available field-based behavioral response studies do not always portray a clear relationship between the received level of sound and the probability of a behavioral reaction. For example, in the case of the blue whales studied in the SOCAL BRS, higher received levels were sometimes associated with a lower probability of reaction (Southall et al., 2019b). This indicates that the received sound level is not necessarily mediating the probability of a behavioral reaction per se, but perhaps only indicating the presence and movement of the sound source. In the case of the blue whales studied in the SOCAL BRS, behavioral reactions were more closely correlated with feeding state than received sound level.

Other studies (e.g., Antunes et al., 2014) also shared similar results: the received level of sound does not always correlate well with the probability of a significant behavioral response. In these cases, other factors likely contributed to the responses, such as repeated encroachment to within a few hundred meters, the proximity of multiple vessels, and cutting in front of the animals' path with the source vessel (often referred to as 'leapfrogging' the animals). These other factors have been studied in the absence of sonar, with respect to vessel traffic and whale watching. For example, killer whales showed behavioral changes in the proximity of multiple vessels (Williams et al., 2014) and when being encroached upon by small boats including kayaks (Williams et al., 2011). Bottlenose dolphins reduced foraging in the presence of boats, independent of sound level (Pirotta et al., 2015) and to avoid intrusive vessels (Lusseau, 2006). Minke whales also decreased foraging in the presence of whale watching vessels (Christiansen et al., 2013). This research provides insight into other factors that may be mediating behavioral responses at low to moderate sound levels during some field-based behavioral response studies discussed in Section 3.1.6.1.

In relation to the conceptual model shown in Figure 36, many of the responses from field-based behavioral studies occur at moderate to low sound levels, in several cases close to the ambient noise level (Miller et al., 2012). It is likely that these reactions are primarily mediated by contextual factors and would fall under the "Context-Based Response" (green curve) in Figure 36. In contrast, results from the controlled exposure sessions using Navy dolphins and sea lions may represent reactions that are primarily mediated by the sound level and could fall under the "Level-Based Response" (blue curve) in Figure 36. This is an important distinction because within the region of context-based response, factors other than sound level, such as proximity and motion of the sound source, are likely to be more important in predicting a significant behavioral response. When received sound is at low to moderate levels, the Navy considers other available factors besides the received level to estimate significant behavioral responses to sonar and sonar-like signals.

3.1.5 Overview of the Approach for Phase 4

The Behavioral Response Functions (BRFs) were developed to estimate numbers of animals that could exhibit significant behavioral responses to Navy At-Sea training and testing activities. Developing the BRFs for Phase 4 involved multiple steps:

- All available behavioral response and controlled exposure studies were examined to understand the breadth of behavioral responses of marine mammals to sonar and sonar-like signals. An overview of the literature considered for analysis is given in Section 3.1.6, along with details on the various sound sources used in each study.
- Captive animal studies were included where received levels in the enclosures could be accurately estimated, and for which responses were scored using the Southall et al. (2021) severity scale.
- Studies that utilized alarms or acoustic deterrent devices (ADDs) were used in Phase 3 analyses but were excluded from Phase 4 analyses. ADDs and alarms are intended to elicit a response, whereas sonar signals may lead to an unintentional behavior. More studies using sonar or sonar-like sources have become available and were used instead since they are more relevant for Navy analyses.
- Data from the behavioral studies were analyzed by looking for significant responses, or lack thereof, for each experimental session following definitions in Section 3.1.2.
- Species groups mostly followed the Phase 3 behavioral groupings along the taxonomic lines of Mysticetes, Odontocetes, and Pinnipeds. The beaked whales and harbor porpoises were combined into a Sensitive Species group.
- Bayesian behavioral response models were utilized to create the response functions described in Section 3.1.6.4 and Appendix G.
- Section 3.1.6.4 presents a summary of the behavioral criteria. For groups that did not have adequate behavioral response data (i.e., sirenians), a surrogate BRF based on behavioral characteristics and taxonomy was assigned.
- Behavioral cutoff conditions are used in Phase 4 (Section 3.1.6.5) but have been updated to reflect the most recent data from the literature and analyses of available range versus received level data.
- The upper bound of the response functions was raised to 200 dB re 1 µPa from 185 dB re 1 µPa in Phase III to account for higher level exposures close to 185 dB re 1 µPa in CEEs that did not lead to a response.

3.1.6 Review of Data Considered

Several papers on behavioral responses of marine mammals to sonar or sonar-like sound sources have been published since the development of the Phase 3 criteria; the studies considered for inclusion in the Phase 4 Navy behavioral response criteria are described below. In addition, most data utilized in the Phase 3 BRFs were included in the Phase 4 analysis and are also briefly summarized below. A few studies included in Phase 3 utilized alarms or ADDs and were therefore excluded in the Phase 4 analysis (See Appendix D). Data that were previously excluded in Phase 3 are not discussed but can be found in the Phase 3 Navy Criteria and Thresholds Report (2017). There were no data considered but excluded in Phase 3 that were included in Phase 4, although data from some captive studies that were not considered in Phase 3 were included in Phase 4. Note, in all studies discussed below and in the Impulsive Sound Sources section (3.2), received levels are reported as dB re 1 µPa root-mean-square (rms) unless otherwise stated.

3.1.6.1 Behavioral Response Field Studies

Behavioral response field studies obtain data under more realistic scenarios (as compared to a controlled laboratory setting); while field experiments are unable to control all variables that are likely mediating behavioral responses, more recent efforts have tried to account for some of these additional variables. These other variables are often referred to as contextual factors (see Section 3.1.4 for more details). In behavioral response studies, contextual factors can be both naturally occurring (e.g., behavioral state prior to exposure) and introduced by the experimental design (e.g., proximity of the source). At moderate to low received levels the correlation between probability of reaction and received level is very poor and it appears that other variables mediate behavioral reactions (e.g., Ellison et al., 2011). Contextual factors that may have influenced responses during earlier behavioral response studies include proximity of the vessel and sound source, physical contact (i.e., tagging), repeated close approaches (within a few hundred meters), multiple vessels, and confined areas (i.e., fjords). In more recent studies, researchers have addressed some of those factors by conducting their experiments in open water, increasing the distance between the source and the animal, increasing the baseline behavioral period between tagging and the first exposure, and not approaching the animal directly with an active source. Additional studies have tagged animals with longer duration tags and observed their responses to real-world Navy training activities, further removing the researchers from the exposure paradigm. Table 17 describes the experimental conditions for each study using data to derive the Navy's Phase 4 behavioral response criteria.

Table 17. Description of experimental conditions used in behavioral response field studies included in the derivation of Phase 4 behavioral response thresholds.

Study	Species	Signal	Signal Frequency	Signal Duration	Signal Interval	Source Level (dB re 1 µPa @ 1 m)	Ship movement	Ship Distance	Exposure Session Duration
SURTASS LFA[1]	Blue whale Fin whale Humpback whale	LFA Sonar	Various 100 - 500 Hz tones/sweeps	< 50 sec	6 - 10 min	160 - 210	Approaching and stationary	Variable	1 - 3 hours
3S[2]	Killer whale Pilot whale Sperm whale	Sonar	6 - 7 kHz hyperbolic upsweep	1 sec	20 sec	158 - 199	Approaching	7 - 8 km to < 1 km	Variable ~30 - 60 min
3S[2]	Killer whale Pilot whale Sperm whale	Sonar	1 - 2 kHz hyperbolic upsweep	1 sec	20 sec	152 - 214	Approaching	7 - 8 km to < 1 km	Variable ~30 - 60 min
3S[2]	Killer whale Pilot whale Sperm whale	Sonar	1 - 2 kHz hyperbolic downsweep	1 sec	20 sec	152 - 214	Approaching	7 - 8 km to < 1 km	Variable ~30 - 60 min
3S2[3]	Humpback whale Northern bottlenose whale	Sonar	1 - 2 kHz hyperbolic upsweep	1 sec	20 sec	141 - 201	Approaching at 45 deg	23 km to < 1 km	40 min
3S3[3]	Sperm whale Pilot whale	Sonar	1 - 2 kHz hyperbolic upsweep	19 sec	1 sec	141 - 201	Approaching at 45 deg	63 km to < 1 km	40 min
3S3[3]	Sperm whale Pilot whale	Sonar	1 - 2 kHz hyperbolic upsweep	1 sec	20 sec	141 - 220	Approaching at 45 deg	63 km to < 1 km	40 min
AUTEC BRS[4]	Blainville's beaked whale	Simulated Sonar	3.2 - 3.75 kHz sweep/tone	1.4 sec	25 sec	152 - 212	Stationary	1 km	~ 15 min
SOCAL BRS[5]	Blue whale Fin whale Cuvier's beaked whale	Simulated Sonar	3.5 - 4.05 kHz sweep/tone	1.6 sec	25 sec	160 - 210	Stationary	1 km	30 min
SOCAL BRS[6]	Blue whale Fin whale Cuvier's beaked whale Risso's dolphin	Real US Navy Sonar	3.5 - 4.5 kHz sweep/tone	1.6 sec	25 sec	235	Approaching	8.1 - 232 km	60 min
Navy Range BRFs[7]	Blainville's beaked whale	Real US Navy Sonar	3.5 - 4.05 kHz sweep/tone	1.6 sec	25 sec	235	Variable	Variable	Variable

[1]Croll et al. 2001, Miller et al. 2000; [2]Miller et al., 2012, Antunes et al. 2014; [3]Kvadsheim et al. 2020; [4]Tyack et al., 2011; [5]Southall et al., 2012; [6]Southall et al., 2019b; [7]Moretti et al. 2014; Jacobson et al. 2022.

3.1.6.1.1 SURTASS LFA SRP

Studies of behavioral responses to low frequency sonar were undertaken in 1997–98 as part of the Navy's Low-Frequency Sound Scientific Research Program (SRP). The Surveillance Towed Array Sensor System (SURTASS) Low-Frequency Active (LFA) exposure studies on blue (*Balaenoptera musculus*), fin (*Balaenoptera physalus*), gray (*Eschrichtius robustus*), and humpback whales (*Megaptera novaeangliae*) (Tyack et al., 1999; Croll et al., 2001) were conducted in three phases. These studies found only short-term responses to low-frequency sound by these mysticetes, including changes in vocal activity and avoidance of the source vessel (Clark & Fristrup, 2001; Croll et al., 2001; Fristrup et al., 2003; Miller et al., 2000; Nowacek et al., 2007). They concluded that changes in distribution of blue and fin whales were due to changes in food distribution, not the occurrence of the LFA source.

Gray whales showed little avoidance if the source was placed offshore of their migratory path, whereas if the source was directly in their migratory path, whales avoided the source by 500–2000 m. However, avoidance responses were relatively short-term and did not impact the migration behavior. Therefore, they were not considered significant behavioral responses. There were no received level data paired with individual behavioral observations available for the gray whale exposures, so these data were not used in the derivation of the Phase 4 behavioral response functions.

No responses were visually observed for humpback whales in Hawaii. Of the 17 singing humpbacks that were exposed to sonar, seven did not respond at all and ten ceased their vocalizations. However, only six of the ten cessations of song were attributable as responses to the LFA sonar. The other four whales stopped singing but then joined another singer or group of whales, which is a well-documented humpback behavior in Hawaiian waters. Even the responses by the six whales that may have responded to LFA were within the standard deviation of all behavior and were therefore not confidently scored as actual responses to sonar.

Data from the blue, fin, and humpback whales were used in the quantitative derivation of the behavioral response criteria in Phase 3 and again in Phase 4.

3.1.6.1.2 3S and 3S2 Studies

Miller et al. (2011; 2012) reported on behavioral responses of pilot whales (*Globicephala melas*), killer whales (*Orcinus orca*), and sperm whales (*Physeter macrocephalus*) off Norway to a Norwegian Navy sonar (Sea Mammals, Sonar, Safety Project [3S]) (Antunes et al., 2014; Kuningas et al., 2013; Miller et al., 2014; Miller et al., 2012; Sivle et al., 2012). The sonar outputs included 1 - 2 kHz up- and down-sweeps and 6–7 kHz up-sweeps; source levels were ramped-up from 152–158 dB re 1 µPa @ 1m to a maximum of 198–214 dB re 1 µPa @ 1m. After a period of twenty minutes to several hours following tag attachment, during which an observation vessel remained with the tagged animal(s), researchers began playbacks of sonar signals, playbacks of sounds made by feeding killer whales, or conducted silent "control" passes of the sonar vessel. At the start of an exposure session, the vessel with the active sonar source began approaching the group from 6–8 km and continued to vector towards the group until within approximately 1 km. The source vessel would then continue upon a straight course until it passed the animal group, often to within a few hundred meters. The source level was always ramped up over the first 10 minutes of the exposure.

Three of the four exposed killer whale groups were foraging prior to the initial sonar exposure; they all ceased to feed and began avoiding the vessel during the first exposure session. Received SPLs corresponding to observed significant behavioral reactions varied from approximately 94 dB re 1 µPa at 8.9 km to 164 dB re 1 µPa at 3.2 km.

Pilot whale behavioral responses occurred at received SPLs between approximately 152 to 175 dB re 1 µPa corresponding to distances of 3.1 km to 90 m, respectively; although during exposures as high as approximately 172 dB re 1 µPa corresponding to a distance of 350 m, no more than minor and brief reactions were observed. Sperm whales responded at received levels between 116 to 156 dB re 1 µPa, corresponding to distances of around 9.0 to 1.8 km, respectively. However, sperm whales exposed to higher levels (up to 166 dB re 1 µPa at 0.9 km) showed no response, or no more than a brief and minor response.

Two follow-on Norwegian 3S studies (3S2 and 3S-ORBS [Off Range Beaked Whale Study]) measured behavioral reactions to sonar sources from humpback whales (*Megaptera novaeangliae*), minke whales (*Balaenoptera acutorostrata*), and bottlenose whales (*Hyperoodon ampullatus*) (Miller et al., 2015; Sivle et al., 2015; Wensveen et al. 2019; von Benda-Beckmann et al. 2019). Similar methods were used as in the first 3S study, including the use of the Norwegian Navy sound source, additional smaller vessels for tagging and behavioral observations, a post-tagging baseline observation period, and the approach of the focal animal by the source vessel during the exposure periods. One difference was that while the initial course of the source vessel was set to approach the animals during the exposures, the vessel would only make small course corrections during the approach and would not change heading to continue vectoring directly at the animals. The 3S-ORBS study was focused on northern bottlenose whales in in an environment with low levels of ambient noise in 2015 and 2016, with one whale tagged with a digital acoustic recording tag (DTAG) in each year, and an additional nine whales tagged with satellite tags. The whales tagged with DTAGs were the focal whales, while the satellite tagged animals provided response data at greater distances from the source vessel.

Both the minke whale and bottlenose whales showed very strong, prolonged responses to the sonar exposures, including avoidance and cessation of feeding that lasted well beyond the period of exposure. These responses began as low as 117 dB re 1 µPa. In the case of the bottlenose whales, the number of other bottlenose whales foraging in the area during and after the exposure also decreased, indicating that these whales in this location may be highly sensitive to noise (Miller et al., 2015; Sivle et al., 2015). The northern bottlenose whales with DTAGs responded at 117, 127, and 130 dB re 1 µPa, while one whale in very close proximity received a very low exposure at 99 dB re 1 µPa at close range and did not respond by avoiding but approached the vessel. These data were included in the Phase 4 behavioral criteria. Although the data from the satellite tagged northern bottlenose whales could not be used in the behavioral response functions as there were not measured received levels associated with the satellite tags, whales seemed to initiate avoidance at distances of 0.8 to 28 km and received levels of 121 to 126 dB re 1 µPa. The few whales exposed at very low levels and long distances (62–99 dB re 1 µPa and 38–346 km) did not respond (Wensveen et al. 2019).

Humpback whale responses were far more varied, and they often didn't respond to exposures that reached SPLs of up to 182 dB re 1 µPa. Those that did respond often responded at lower received levels by avoiding the sound source, changing their dive profile, and ceasing to forage. There was no apparent difference in response during the ramp-up versus no-ramp-up trials. Of the four animals with significant behavioral responses, two animals responded to the ramp-up trials (at 125 and 132 dB re 1 µPa) but not to the no-ramp-up trials, and one animal responded to both trials (at 127 and 165 dB re 1 µPa, respectively).

These data were included in the derivation of the Phase 3 and Phase 4 behavioral criteria.

3.1.6.1.3 3S3 Study

In 2016, 2017, and 2019, the 3S team conducted a third phase of the 3S study (3S3; Lam et al. 2018a, 2018b; Kvadsheim et al. 2020). This phase was focused on addressing some of the contextual variables that may contribute to a behavioral response, with a focus on sperm whales and pilot whales. First, to address the issue of the distance to a source versus the received level of the signal (range versus RL), the team used the same 1-2 kHz upsweep signal but at two different maximum source levels: Moderate Source Level Pulsed Sonar (MPAS), with a source level ranging from 141 to 201 dB re 1 µPa, and High Source Level Pulsed Sonar (HPAS), with a source level ranging from 154 to 214 dB re 1 µPa. This allowed the source vessel to approach the tagged focal animal(s) from different distances while achieving similar received levels at the animal. These signals were otherwise identical to the 1-2 kHz upsweep signal used in the previous 3S experiments. In 2019, a real Norwegian navy ship was added to the experiment, in addition to the towed sonar source deployed from the research vessel, with even higher source levels (Extra High Source Level Pulsed Sonar [XHPAS], 165 - 220 dB re 1 µPa) that could approach from a greater distance. Second, to investigate how signal duration and the resulting Sound Exposure Level might influence a behavioral response, a Continuous Active Source (CAS) signal was also implemented, with a signal duration of 19 sec instead of 1 sec but with the same lower source level as the MPAS signal (141-201 dB re 1 µPa). The researchers could then assess signal duration, the received SPL, and the received SEL (which would be higher for the CAS and HPAS signals) to determine what factors might best predict a behavioral response (Curé et al. 2021; Isojunno et al. 2020, 2021). These three signal types were randomized in the order in which they were presented to each tagged animal(s). A no signal control pass was also included, and was conducted first, when possible, for a total of up to four passes per tagged animal(s). Multiple animals may have been tagged prior to the onset of the exposures, with one animal selected as the focal animal. This also allowed animals to receive the different signals at different distances, since proximity with the source vessel was only maintained for the focal animal during each set of passes, so the other animals could move away over the period of exposures. Finally, an extended baseline period of four hours was conducted between the tagging and the first no-sonar pass to allow the animals' behavior to fully return to pre-tagging levels before the start of the experimental passes.

Seven sperm whales were tagged in 2016. All but one had no-signal passes with the source vessel, but only five had subsequent exposure passes. One of those whales received two signal types (MPAS and CAS), and the remaining four were exposed to all three signal types. Only one of these whales had a moderate response to an MPAS exposure at 116 dB re 1 µPa with a cessation of foraging behavior. Seven focal sperm whales were also tagged in 2017, with an additional four sperm whales tagged for ancillary data in four of the experiments. Just as in 2016, all but one group received the no-signal passes with the source vessel, and then five of the seven groups or individuals received all three signal types, while two groups/individuals received two signal passes. There were eight moderate-level responses in 2017, but only one lasted the duration of the exposure; this was to an MPAS exposure at 147 dB re 1 µPa with avoidance, a change in dive behavior, and a cessation of foraging. In 2019, 10 focal sperm whales were tagged (some with two tags each to ensure data was collected for the duration of each experiment), and five additional sperm whales were tagged for ancillary data. Three animals received the no sonar control pass (for one animal that was the only pass before the tag fell off); nine received a distant ship exposure from the real navy vessel plus at least one close exposure, while two of those animals received an additional close pass. Three whales did not respond to any of the exposures. Three responses occurred to no-sonar passes, while 16 sonar exposures (across seven whales) elicited some type of behavioral response. Of those, two whales demonstrated avoidance or changes in behavior that lasted longer than the exposure period.

One whale responded to two different XHPAS exposures at 142 dB and 170 re 1 µPa with avoidance and cessation of resting or feeding, while the other whale also responded to an XHPAS exposure with a prolonged change in their dive profile and minor avoidance at 158 dB re 1 µPa. The remainder of the responses were either minor or moderate but lasted less than the duration of the exposure (Curé et al. 2021). All 3S3 data were included in the Phase 4 behavioral criteria.

3.1.6.1.4 AUTEC BRS

Tyack et al. (2011) found a significant reduction in foraging dives of Blainville's beaked whales (*Mesoplodon densirostris*) during periods of sonar operation hydrophones at the Atlantic Undersea Test and Evaluation Center (AUTEC) in the Bahamas, and further found that whales that continued to dive concurrently with sonar were 2.2 – 28.9 km away from the source, with SPLs of 101 to 157 dB re 1 µPa. In addition, an individual beaked whale was also tagged with a satellite tracking tag prior to a Navy exercise (Tyack et al., 2011). During sonar, the animal moved ~17 km farther from the center of the range than it was before the sonar period and received a maximum SPL of 146 dB re 1 µPa. The animal returned to the range within 2 to 3 days after the cessation of sonar operations. Another beaked whale was tagged with a DTAG and exposed to a playback of mid-frequency active sonar (MFAS) (Tyack et al., 2011) using a simulated sonar signal of ~3.5 kHz that had similar frequency characteristics to U.S. Navy tactical sonar (see Table 17, but at lower source levels [up to 212 dB re 1 µPa @ 1 m]). This source was deployed from a stationary vessel positioned about 1 km from where a beaked whale had begun a foraging dive. This whale was exposed to MFAS in the middle of a foraging dive; it stopped clicking at an SPL of 138 dB re 1 µPa and began a slow ascent while moving away from the sound source. These data were included in deriving the Phase 3 and Phase 4 behavioral criteria.

3.1.6.1.5 SOCAL BRS

A behavioral response study conducted on and around the Navy range in Southern California (SOCAL BRS) observed reactions to sonar and similar sound sources on a number of species: Cuvier's beaked whales (*Ziphius cavisrostrus*), a Baird's beaked whale (*Berardius bairdii*), blue whales, fin whales, and Risso's dolphins (*Grampus griseus*) (DeRuiter et al., 2013; Goldbogen et al., 2013; Southall et al., 2011; Southall et al., 2012; Southall et al., 2013; Southall et al., 2014; Southall et al. 2019b). During most of the SOCAL BRS experiments, a simulated mid-frequency sonar was deployed, but in 2013, 2014, 2015, and 2016, several animals were also exposed using actual MFAS from U.S. Navy vessels and, in a few cases, helicopter-dipping sonar. One or two animals were tagged with data-recording tags (e.g., DTAGs), and then an observation period from 45 minutes (for mysticetes) up to two hours (for odontocetes) was conducted to obtain baseline behavioral data. The simulated source vessel then positioned itself about 1 km from the tagged focal animal and deployed the sound source (the real Navy ship was positioned tens of kms away). Like the 3S studies, the SOCAL BRS implemented a ramp-up protocol in which they started the exposure with a source level of 160 dB re 1 µPa @ 1 m and increased rapidly over a 5- to 10-minute period, up to 210 dB re 1 µPa @ 1 m for the simulated sonar signal. However, unlike the 3S study, the vessel with the simulated source did not approach the focal animal; once it was positioned, small adjustments were made to keep the sound source vertical in the water column, but otherwise it remained stationary. The real Navy ships did approach the animals and did not ramp up their source, but they started far enough away from the animals that the approaching sound was like a ramp up of a stationary source.

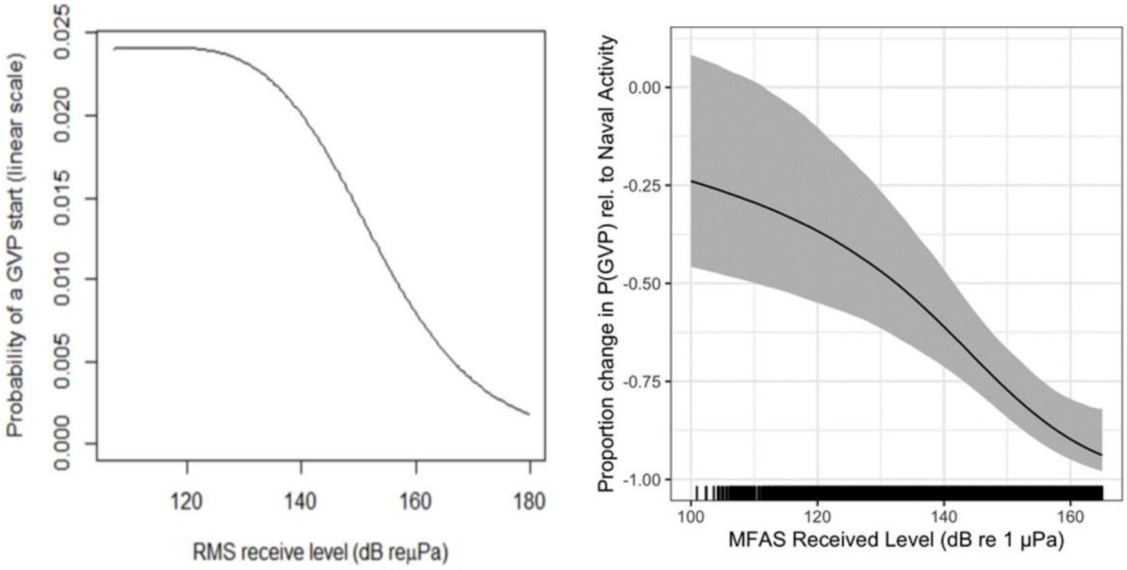
Behavioral responses during the SOCAL BRS varied widely both within and across species. Many of the blue whales did not respond, even at received SPLs up to 165 dB re 1 µPa. However, those that did respond often responded at lower received SPLs (mean = 123 dB re 1 µPa).

There was behavioral context associated with whether animals responded, for example, deep feeding blue whales were more likely to respond than shallow feeding or traveling animals (Goldbogen et al., 2013). None of the fin whales exposed to either the simulated or real sonar sources demonstrated more than a brief or minor response regardless of their behavioral state. All beaked whales exposed to the simulated sonar responded by avoiding the source, ceasing their foraging dives, and otherwise changing their dive behavior (DeRuiter et al., 2013; Stimpert et al., 2014). However, none of the beaked whales exposed to real Navy sonar at greater distances (whether intentionally or incidentally) responded, even when the received levels were like the levels from the simulated sonar. In general, although the responses to simulated sonar were varied across individuals and species, most of the animals exposed to real Navy sonar did not respond; these exposures occurred at distances beyond 10 km and were up to 60 – 100+ km away (DeRuiter et al., 2013; Southall et al. 2014). The exception was one blue whale that responded to the real Navy helicopter-dipping sonar at 143 dB re 1 µPa with moderate cessation of foraging and moderate avoidance.

These data were included in the derivation of the behavioral criteria; the blue whale and beaked whale data were included in Phase 3. In addition to that data, the fin whale and Risso’s dolphin data were also included in Phase 4.

3.1.6.1.6 Navy Range Risk Functions

Moretti et al. (2014) used seafloor-mounted hydrophones to estimate Blainville's beaked whale foraging dives before, during, and after a Navy training exercise with MFAS at AUTEC (Figure 37). They developed a generalized additive model of the probability of a beaked whale dive occurring anywhere on the range, and then determined the probability of a dive occurring in the presence of sonar. This effort was replicated at the Pacific Missile Range Facility (PMRF) in Hawaii for Blainville's beaked whale dives before, during, and after six Navy training exercises with MFAS (Jacobson et al., 2022). The resulting reduction in foraging dives from the period just before the MFAS activity to the period with MFAS were comparable from both ranges, and data from both were extracted and included in Phase 4 risk functions.



- Probability functions taken from Moretti et al. (2014, left) and Jacobson et al. (2022, right) indicating the decrease in the probability of a group vocal period (i.e., foraging dive) occurring as received levels increase.
- Note the x- and y-axes are at different scales.
- The black bars on the bottom of the right plot indicate data points exist for those received levels.

Figure 37. Probability functions from Moretti and Jacobson.

3.1.6.2 Captive Animal Behavioral Studies

Captive animal studies examine behavioral responses under controlled conditions. These studies allow researchers to vary the factor of interest while holding other factors stable. The received level of sound is the primary factor of interest in most of the experiments conducted to date. Within captive animal studies, the probability of behavioral response seems to be well correlated with received level, indicating a primarily level-based response. Studies that used pingers or other alarm-type signals that are intended to illicit a response were excluded from this analysis; only studies that used sonar, or sonar-like signals, were included. For studies that were investigated but not utilized, see Appendix D. Table 18 describes the experimental conditions for each study in which data were used to derive the Navy's Phase 4 behavioral response criteria.

Table 18. Description of experimental conditions used in captive animal behavioral studies.

Study	Signal	Signal Frequency	Signal Duration	Signal Interval	Source Level (dB re 1 μPa @1 m)	Exposure Session Duration
Bottlenose dolphin CES [1]	Simulated Sonar	3.25 − 3.45 kHz sweep/tone	1 sec	30 sec	132–202	5 min
California Sea Lion CES [2]	Simulated Sonar	3.25 − 3.45 kHz sweep/tone	1 sec	30 sec	142–202	5 min
Hooded seal CES [3]	Simulated Sonar	1.3 − 1.7 kHz upsweep	1 sec	10 sec	134–194	6 min
Hooded seal CES [3]	Simulated Sonar	3.7 − 4.3 kHz upsweep	1 sec	10 sec	134–194	6 min
Hooded seal CES [3]	Simulated Sonar	6 – 7 kHz upsweep	1 sec	10 sec	134–194	6 min

[1] Houser et al., 2013a; [2] Houser et al., 2013b; [3] Kvadsheim et al., 2010

3.1.6.2.1 Dolphin and Sea Lion Controlled Exposure Studies

Controlled-exposure studies (CESs) were conducted with 30 U.S. Navy bottlenose dolphins and 15 California sea lions (*Zalophus californianus*) at the Navy Marine Mammal Program facility specifically to study behavioral reactions (Houser et al. 2013a; Houser et al. 2013b). These studies were designed to expose animals at a wide variety of received levels with the specific intent of building behavioral dose-response functions. Due to their history of training, food reinforcement, and housing in a noisy bay environment, Navy animals are potentially less sensitive to noise exposure than wild animals. In both studies, animals were trained to swim across a pen, touch a target paddle, and return to the starting location. During transit, a simulated mid-frequency sonar signal was played at an SPL previously assigned to each animal. Dolphins received six different exposure levels ranging from 115-185 dB re 1 μPa and sea lions received five different exposure levels ranging from 125-185 dB re 1 μPa. The transducer was located 1 m behind the target paddle so that the subject animal would have to close their distance to within 1 m of the transducer that emitted the simulated sonar signal a few seconds before. Video and audio were recorded of the session and observers that subsequently scored the sessions for behavioral responses were blind to the exposure conditions.

Behavioral reactions included increased respiration rates, fluke or pectoral fin slapping (dolphins), prolonged submergence (sea lions), and refusal to participate, among others. Of the 20 dolphins that received exposures of 115–160 dB re 1 μPa in ten trials each, there were only six significant behavioral reactions out of the 200 trials; these responses occurred at the 130 (1), 145 (3), and 160 (2) dB re 1 μPa treatments. Bottlenose dolphins were more likely to respond to the initial trials but habituated to the sound over the course of ten trials, except at the highest received levels (175 and 185 dB re 1 μPa). One out of three California sea lions exposed to the 125 dB re 1 μPa treatment and one out of three exposed to the 155 dB re 1 μPa treatment showed significant reactions on all ten exposure trials, while the other four individuals at the same levels did not demonstrate significant responses. Sea lions showed consistent significant responses on almost all trials at the 170 and 185 dB re 1 μPa (rms) levels. Unlike dolphins, sea lions did not habituate over the course of ten exposure trials and younger animals were more likely to respond than older animals.

This indicates that age or life experience may play a large role in mediating responses to noise exposure in sea lions. In both the sea lion and dolphin CEEs, the probability of behavioral reactions was well correlated with received level indicating a primarily level-based response.

These data were included in the derivation of the Phase 3 and Phase 4 behavioral criteria.

3.1.6.2.2 Hooded Seal Controlled Exposure Study

Captive hooded seals (*Cystophora cristata*) were exposed to tonal signals in the 1 to 7 kHz band to determine the received SPL at which these animals would respond (Kvadsheim et al., 2010). Hooded seals were exposed to three different mid-frequency upsweeps (1.2–1.7 kHz, 3.7–4.3 kHz, and 6–7 kHz) that started at a source level of 134 dB re 1 µPa @ 1 m and increased to 194 dB re 1 µPa @ 1 m; received levels were 10–27 dB lower depending on the animal's position in the netted enclosure. The animals' dive frequency and time spent at surface were monitored during the exposures, and changes to these were used as metrics of response. The seals showed no response to received SPLs below about 160 dB re 1 µPa; once SPLs were between 160–170 dB re 1 µPa, the seals began actively avoiding the sound source (at 5 m depth) by reducing their dive activity, rapidly swimming at the surface, and floating with their heads out of the water (Kvadsheim et al., 2010).

These data were included in the quantitative derivation of the Phase 3 and Phase 4 behavioral criteria.

3.1.6.2.3 Harbor Porpoise Behavioral Response Studies

Over the last two and a half decades, eighteen studies at the Sea Mammal Research Company (SEAMARCO) have been conducted to test the behavioral responses of harbor porpoises to a variety of acoustic signals. Some of these have been dedicated behavioral response studies (Table 19: Kastelein harbor porpoise behavioral response study signal characteristics), while others have secondarily observed behavioral responses during hearing studies. In all cases, the studies have quantified and (when possible) statistically analyzed the changes in respiration rates, swimming speeds, distance from the sound source, and number of jumps during baseline and exposure periods as metrics of behavioral responses. The sound sources studied have included signals that mimic real navy sonar sources from the U.S. and other countries, acoustic alarms and deterrents, and pure tones, all in the mid (2 – 10 kHz) and high (10+ kHz) frequency ranges, although the studies using alarms and deterrents were excluded from this analysis. These studies have also examined the impacts of harmonics, comparing responses to pure tone signals against tones or sweeps with harmonics that might be more detectable by harbor porpoises. The effect of duty cycle has also been tested, with studies ranging from short duration signals with low duty cycles to longer signals or continuous duty cycles. Sound pressure levels were carefully measured across the breadth of the enclosure, allowing precise received level estimates for each type of response. Responses occurred at SPLs from 86 to 143 dB re 1 µPa (mean 122 dB re 1 µPa) across all the signal types and duty cycles, while there was no response to signals with SPLs from 98 to 148 dB re 1 µPa (mean 129 dB re 1 µPa). To apply the Southall et al. (2007) severity scaling to these data (used in this case for more direct comparison of response severity with field studies), it was determined that changes in respiration rates were the least severe response (3), increased swim speeds were the next most severe (4/5), distance from the sound source was next as an approximation for avoidance (6), and jumping was the most severe (7), as this was a behavior rarely seen in baseline or non-experimental periods. The responses in these papers were scored accordingly, and the results were incorporated into the Sensitive behavioral risk function for Phase 4.

Table 19. Kastelein harbor porpoise behavioral response study signal characteristics.

Study	Signal	Signal Frequency (kHz)	Signal Duration (s)	Signal Interval (s)	Sound Pressure Level (dB re 1 μPa)	Exposure Session Duration (min)
Kastelein et al. 2008	HFAS CAS	50	continuous	continuous	113	15
Kastelein et al. 2011	MFA upsweep	6 – 7	1	3 – 7	106	30
Kastelein et al. 2013e	MFAS Helo	1.33 – 1.43	1.25 – 10	180	124 – 144	60 – 90
Kastelein et al. 2014b	LFA upsweep/ downsweep	1 – 2	1	3 – 7	114 – 123	30
Kastelein et al. 2014b	MFA upsweep/ downsweep	6 – 7	1	3 – 7	107	30
Kastelein et al. 2015d	HFAS	25	0.05	2	71–148	30
Kastelein et al. 2015e	HFAS	25	multiple	multiple	76 – 153	30
Kastelein et al. 2018b	MFAS	3.5 – 4.1	1.6	0.06 (96% duty cycle)	83 – 143	30
Kastelein et al. 2018b	MFAS	3.5 – 4.1	1.6	58.4 (2.7% dc)	119 – 143	30
Kastelein et al. 2019e	MFAS Helo	1.33 – 1.43	1.25	14.4	96 – 98	30

3.1.6.2.4 Harbor Seal Behavioral Response Studies

Several studies were conducted at SEAMARCO on harbor seals, often using the same signal paradigms (frequency, duration, and duty cycle) that were used with harbor porpoise behavioral response studies (Table 20). These included mid- and high-frequency tones, broadband alarms and acoustic deterrents, and underwater communication signals; however, as before, studies using alarms and acoustic deterrents were excluded from this analysis. Sound pressure levels in the enclosures ranged from 105 to 160 dB; responses occurred to signals with SPLs from 107 to 160 dB re 1 µPa, whereas in other experimental trials, there was no response to signals with SPLs from 134 to 156 dB re 1 µPa. The behavioral responses in these studies were scored similarly to the responses by harbor porpoises, where increased respirations or lifting their head out of the water was the least severe (3), avoidance of the source by remaining on the far side of the pool was more severe (6) and jumping or hauling out was the most severe (8). These results were incorporated into the pinniped behavioral risk function for Phase 4.

Table 20. Kastelein harbor seal behavior response study signal characteristics.

Study	Signal	Frequency (kHz)	Signal Duration (s)	Signal Interval (s)	Sound Pressure Level (dB re 1 µPa)	Exposure Session Duration (min)
Kastelein et al. 2006b	tone	8	0.25	5	$129 - 142$	45
Kastelein et al. 2006b	tone	16	0.25	5	$117 - 134$	45
Kastelein et al. 2006b	tone	32	0.25	5	$119 - 135$	45
Kastelein et al. 2006b	tone	45	0.25	5	$128 - 141$	45
Kastelein et al. 2006c	data transmission	12	multiple	multiple	$105 - 118$	15
Kastelein et al. 2015f	HFAS	25	multiple	multiple	$125 - 158$	30

3.1.7 Marine Mammal Behavioral Species Groups

Data on behavioral responses to sonar and sonar-like signals exist for relatively few species, which necessitates that species be divided into groups of related animals, either phylogenetically or by documented species sensitivities and responses. The four primary groups for application of the Phase 4 criteria are Mysticetes, Odontocetes (not including beaked whales or harbor porpoises), Pinnipeds, and Sensitive Species, which includes beaked whales and harbor porpoises. While beaked whales and harbor porpoises are odontocetes, they will continue to have a separate risk function in Phase 4 due to their documented sensitivity to sonar and sonar-like signals. Little to no behavioral response data exists for manatees; as such, they are assigned to a surrogate behavioral criteria group, the Mysticetes. Likewise, no behavioral response data exist for sea otters or polar bears, so they are also assigned to a surrogate behavioral criteria group, the Pinnipeds.

The Odontocete group includes all oceanic toothed whales, with the exclusion of beaked whales and harbor porpoises. All odontocetes use echolocation to navigate and hunt for prey, and in some cases for communication. Many odontocetes also vocalize using whistles and burst pulses, and these can range from simple flat whistles to complex, multi-part vocalizations that may be pod- or even individually-specific (Ford & Fisher, 1982; Lammers et al., 2003; Richardson et al., 1995). Due to similarities in hearing and vocalization traits and close taxonomic links, odontocetes (excluding beaked whales and harbor porpoises) are assigned to a single behavioral criteria group.

The Pinniped group is comprised of all phocids, otariids, and odobenids. Animals within this group spend their time both on land and at sea, although in varying degrees for different species (Reeves et al., 2002). While some species are found in remote locations, the dependence on land causes many pinniped species to be in close association with humans. Pinnipeds produce vocalizations in air and under water; these include calls between mothers and pups, alarm calls, mating displays, and aggressive exchanges between males, among others (Schusterman et al., 2001). Due to similarities in acoustic traits and close taxonomic links, pinnipeds are assigned to a single behavioral criteria group. No data can be found on polar bear or sea otter reactions to underwater sounds, especially those from sonar or sonar-like signals. Polar bears spend a good deal of their time on land or ice and little time with their heads submerged below the surface while swimming or hunting. Sea otters live in shallow coastal areas and spend a great deal of time floating at the surface or conducting short foraging dives. Sea otters and polar bears are both assigned to the Pinniped behavioral criteria group.

Mysticetes produce low- and mid-frequency vocalizations, from 20 Hz up to 20-30 kHz (Richardson et al., 1995). These calls range from simple sweeps and moans to complex songs, and due to their lower frequency and high amplitude (120-190 dB re 1 µPa @ 1 m) they can be detected for hundreds of kilometers in the ocean. Due to similarities in acoustic traits and close taxonomic links, mysticetes are assigned to a single behavioral criteria group. For sirenians (manatees and dugongs), vessel noise may also be a concern (Miksis-Olds et al., 2007), but there is little information available about manatee responses to other noise sources, including active sonar. Mysticetes share important behavioral traits (e.g., grazing); therefore, manatees are assigned to the Mysticetes behavioral criteria group.

Beaked whales (family Ziphiidae) tend to avoid vessels and underwater noise (Barlow & Gisiner, 2006). Due to several mass stranding events of beaked whales in proximity to Navy training events (D'Amico et al., 2009), this group has been deemed highly sensitive to sonar and other active acoustics and are therefore considered separately from the other odontocetes. Similarly, harbor porpoises have been shown to be highly sensitive to underwater noise, including acoustic pingers (Kastelein et al., 2000; Teilmann et al., 2006), pile driving (Kastelein et al., 2013c; Tougaard et al., 2009), and impulsive sounds (Kastelein et al., 2013d). Due to these noted sensitivities, beaked whales and harbor porpoises are considered separately from the other odontocetes and are assigned to the Sensitive Species behavioral criteria group.

3.1.8 Behavioral Response Functions and Thresholds for Sonar and Sonar-like Signals

Behavioral response studies that were designed to record behavioral observations and contained detailed data on reactions at specific received sound levels were used quantitatively in the derivation of the Phase 4 behavioral criteria. Captive data were incorporated for which behavioral responses could be scored using the Southall et al. (2021) severity scale.

Data from the applicable studies were obtained from published materials. Exposure and behavioral response data for the 3S, BRS, startle response, and real Navy training response studies were also directly discussed with the researchers. The Bayesian methodology and computer model used for the Phase 4 criteria were developed by the Centre for Research into Ecological and Environmental Modelling (CREEM) at the University of St. Andrews (Bouchet et al. 2020; 2021). The methodology used to develop these models is described in detail in Appendix G. While the models provided the flexibility and statistical framework to use model-selected species groupings, as discussed in Section 3.1.7, pre-selected species groupings were used. Similarly, the models provided the framework to use either monophasic or biphasic response functions. Appendix G provides more detail about the flexibility and functionality of the computer model. Although all the response functions are biphasic, the shapes of some still resemble a monophasic curve, indicating that there was less statistical support in that model for the full biphasic function. A biphasic curve biphasic curve is a series of two sigmoidal curves that approximates the shape of the illustration in Figure 36 (Ellison et al., 2011), which acknowledges that significant reactions at lower to moderate received levels are likely mediated by factors other than sound level. Finally, for each behavioral response function, one and half to two million iterations were run to assure convergence of the results (i.e., the final curves are statistically supported).

3.1.8.1 Sensitive Species

Beaked whales and harbor porpoises have both been found to be particularly sensitive to sonar and sonar-like signals, so data on behavioral responses for these species were combined to create a

Sensitive Species behavioral response function. The beaked whale behavioral response data from the BRS and 3S studies were limited, and some responses occurred at relatively low received SPLs (Table 21). However, these are again likely tied to the context of the exposures. In the 3S study the vessel was directed at the bottlenose whale and continued vectoring around the animal, while in the SOCAL BRS there were multiple vessels within 1–3 km of the animals. It should be noted that the third SOCAL BRS beaked whale that did not respond (Table 21) was exposed to MFA sonar from an actual Navy vessel located over 65 km away from the animal. Although not included in this dataset, another beaked whale in the SOCAL BRS was incidentally exposed to real Navy sonar during a simulated sonar experiment. It did not respond to the real sonar, even though it occurred at received levels like those received during the simulated sonar playback when it did respond (DeRuiter et al., 2013). This may provide some evidence that the proximity of the source rather than the received level alone contributes to the response of the animal for animals likely to be familiar with sonar, since these exposures occurred at similar received levels but with different outcomes. However, many of the northern bottlenose whales in a low ambient noise environment responded at a variety of distances, so some familiarity to the sound may mediate a response at greater distances while a novel sound at greater distances may cause a response.

Table 21. Beaked whale and harbor porpoise data relied upon for quantitative assessment of behavioral response.

Species	Study	Individuals	Exposures	Range of Exposure Received Levels (dB re 1 µPa)	Significant Responses	Range of Response Received Levels (dB re 1 µPa)	Distances of Responses (km)
Bottlenose Whale	3S (Sivle et al., 2015; Wenseveen et al., 2019)	4	4	72 – 151	3	117 – 130	0.81 – 16.8
Cuvier's and Baird's Beaked Whale	BRS (DeRuiter et al., 2013; Stimpert et al., 2014; Southall pers comm. 2014)	4	5	91 –143	3	95 – 100	1 – 2.7
Blainville's Beaked Whale	(Tyack et al., 2011)	1	1	< 100 – 147	1	138.4	1
Blainville's Beaked Whale	(Moretti et al., 2014)	Unknown	> 106	120 – 180	NA	100 – 200	NA
Blainville's Beaked Whale	PMRF BRF (Jacobson et al., 2022)	unknown	100's	90 – 165	NA	100 – 200	NA
Harbor Porpoise	Captive CEE (Kastelein various)	9	19	71 – 153	9	106 – 143	NA

In addition to the BRS and CEE data (Table 21), the Moretti et al. (2014) and Jacobson et al. (2022) data were also used in the derivation of the beaked whale BRF. The Moretti et al. (2014) and Jacobson et al. (2022) data are from actual multiplatform, multiday ASW training. The data from the Generalized Additive Models (GAMs) developed to estimate the decrease in probability of a foraging dive were used rather than the Generalized Linear Model (GLM) fit to be most consistent with the other data sources used herein to derive BRFs; the GAM data represents the response that was measured, whereas the GLM line fit was a smoothed function derived to fit between 0 and 100 percent probability of response. The GAM function extends from 120 to 180 dB re 1 µPa and has a 50 percent probability of response at a SPL of 150 dB re 1 µPa (Moretti et al., 2014) and 132 dB re 1 µPa (Jacobson et al., 2022). Note that both GAM functions were recalculated from 100 to 200 dB re 1 µPa for the purposes of being subsampled for the Navy behavioral response function, and so the full function was subsampled and not just values up to 165 or 180 dB re 1 µPa as in the published papers. This is reflected in Table 21 in the "Range of Response Received Levels" column values.

Although the Moretti et al. (2014) and Jacobson et al. (2022) data are different than other data used in the derivation of behavioral response functions, without their use to fill in responses at higher received levels, the functions would have been fit based solely on low to moderate level exposures from proximal sources such as most of those from the BRS/3S2 datasets.

The Moretti et al. (2014) and Jacobson et al. (2022) curves provide "observations" of the proportions responding at higher received levels. Additionally, as discussed above, these observations were during actual multi-ship, multi-day ASW events on Navy ranges. Therefore, to equally weight the contributions from the ten exposures in the BRS and 3S field studies and the Moretti et al. (2014) and Jacobson et al. (2022) GAM data, the GAMs were sampled ten times equally across the curve (e.g., the curve was subsampled at ten random but equally spaced probabilities to get the corresponding received levels).

All harbor porpoise data were derived from controlled exposure experiments on captive animals; there are no data available on responses of wild porpoises to sonar or sonar-like signals. For harbor porpoises, a large enough aggregation of controlled exposure studies to captive animals exists that they data could be included here in the development of the sensitive species risk function. Eight studies were conducted at SEAMARCO over 25 years using a variety of sonar and sonar-like sources. Note that all these exposures occurred in an enclosed area and so at relatively close range. Some individuals were tested more than once, for different sources or exposure paradigms. Each individual is represented in the Navy Behavioral Response function only once per study, at the lowest received level at which a moderate to severe response occurred; therefore, individuals may have been included more than once if they participated in more than one study.

Responses in these species occurred at a range of received levels from 95 – 138 dB re 1 µPa, with a mean response received level of 121 dB re 1 µPa. The 50 percent response level for the sensitive species behavioral response function is at 133 dB re 1 µPa. Note that in Figure 38 and all following response function figures, the credible interval for a Bayesian function is like a confidence interval in frequentist statistics.

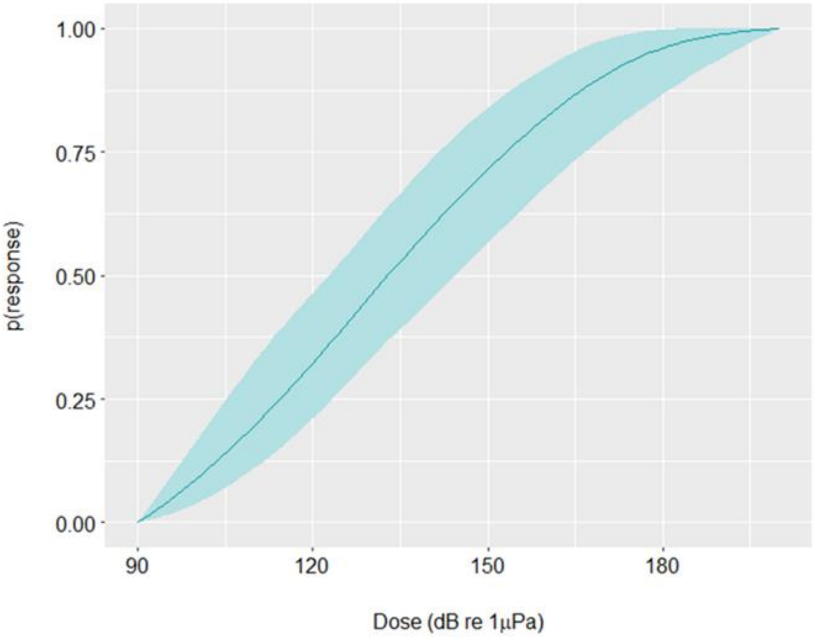


Figure 38. Phase 4 Sensitive Species Biphasic Behavioral Response Function, with the 50 percent credible interval shaded in teal.

3.1.8.2 Odontocetes

Overall exposure levels are given for each species/study group (Table 22). Responses occurred at received levels ranging from 94 to 185 dB re 1 µPa, and the mean of the response data was 150.6 dB re 1 µPa. This wide variation in received levels at which responses occurred indicates the contextually- and species-dependent nature of behavioral responses within field studies.

Killer whales responded in some cases at low levels, but this occurred in a very specific scenario (in a closed fjord with an approaching vessel and a calf present) so the results may not be broadly applicable; however, these are currently the best available data for this species. The sperm whales demonstrated a variety of responses to a broad range of received levels and distances. Neither of the Risso's dolphins responded, but their exposures occurred at long distances; in contrast, few pilot whales responded to exposures at close range. All these field data were fit using the methods described above. However, for the bottlenose dolphin controlled exposure study (CES) data, a modified dose-response function was developed in which low-severity responses were considered non-responses and moderate and severe responses were considered significant responses. This modified function was subsampled 30 times to account for the 30 individuals in the CES study so individuals from the CES and field studies were all represented once. The resulting odontocete response function is shown in Figure 39, with a 50 percent probability of response at 168 dB re 1 µPa.

Table 22. Odontocete data relied upon for quantitative assessment of behavioral response.

Species	Study	Individuals	Exposure Sessions	Range of Exposure Received Levels (dB re 1 µPa)	Significant Responses	Range of Response Received Levels (dB re 1 µPa)	Distances of Responses (km)
Killer Whale	3S (Miller et al., 2011; Miller et al., 2014; Miller et al., 2012)	4	8	71 – 174	6	94 – 164	0.4 –2.5
Sperm Whale	3S, 3S3 (Miller et al., 2011; Miller et al., 2012; Kvadsheim et al. 2020)	27	77	73 – 179	15	99.3 – 169.8	0.65 –12.3
Pilot Whale	3S (Antunes et al., 2014; Miller et al., 2011; Miller et al., 2012)	6	14	70 –180	4	115 –159	0.08 –0.3
Bottlenose Dolphin	CES (Houser et al., 2013a)	30	30	115 –185	12	130 –185	NA
Risso's Dolphin	SOCAL BRS (Southall et al. 2014)	2	2	128 –131	0	NA	NA

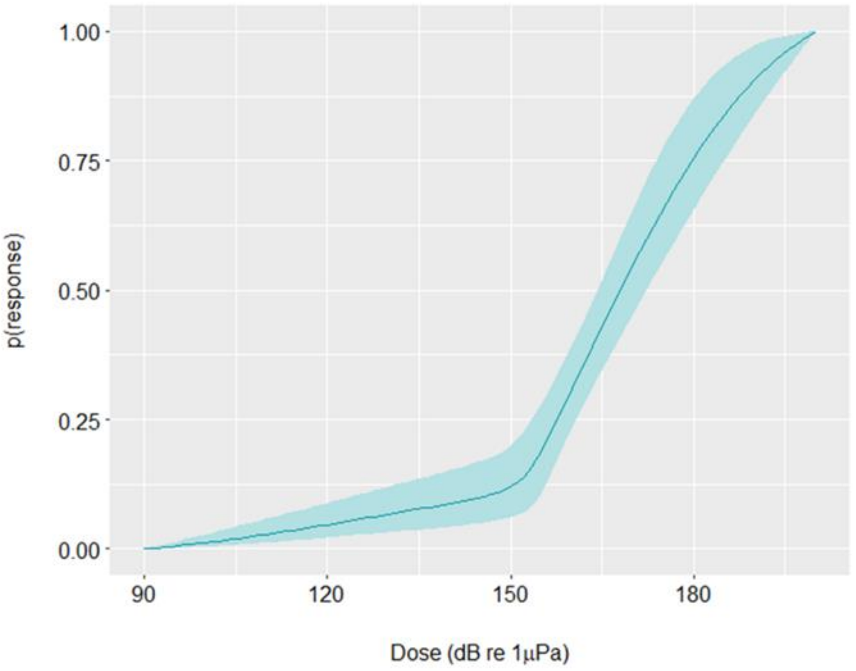


Figure 39. Phase 4 Odontocete Biphasic Behavioral Response Function with the 50 percent credible interval shaded in teal.

3.1.8.3 Pinnipeds (In-Water)

All in-water pinniped data were derived from controlled exposure experiments on captive animals; there are no data available on responses of wild pinnipeds to sonar or sonar-like signals. There are also no data available for in-air exposures to sonar or sonar-like signals. Overall exposure levels are given for each species/study group (Table 23; responses occurred at received levels ranging from 107 to 185 dB re 1 µPa, and the mean of the response data was 154 dB re 1 µPa. Hooded seals were exposed to increasing levels of sonar until an avoidance response was observed. The harbor seals were exposed to a variety of contexts, frequencies, and received levels. For the California sea lion data, a modified dose-response function was created in which low severity responses were considered non-responses and moderate and severe responses were considered significant responses, following Houser et al. (2013b); this response function was sampled 15 times (once per individual) to allow each individual to be represented once as was done for the other captive studies. The resulting response function is shown in Figure 40 and has a 50 percent probability of response at 156 dB re 1 µPa.

Table 23. Pinniped data relied upon for quantitative assessment of behavioral response.

Species	Study	Individuals	Exposure Sessions	Range of Exposure Received Levels (dB re 1 μPa)	Significant Responses	Range of Response Received Levels (dB re 1 μPa)	Distances of Responses (km)
Hooded Seal	CES (Kvadsheim et al., 2010a)	4	12	110 – 170	12	160 – 170	NA
California Sea Lion	CES (Houser et al., 2013b)	15	15	125 – 185	9	125 – 185	NA
Harbor Seal	Captive CEE (Kastelein various)	16	NA	107 – 158	9	107 – 158	NA

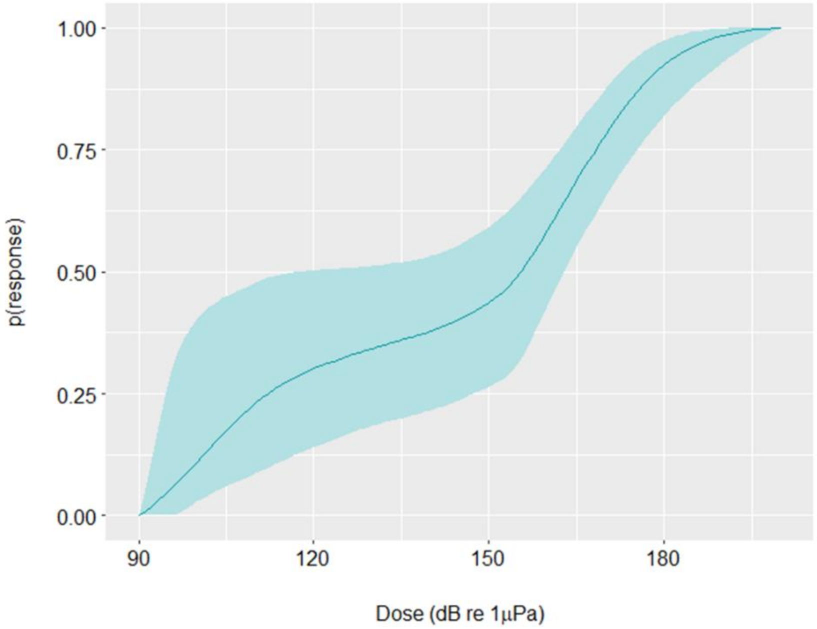


Figure 40. Pinniped In-Water Biphasic Behavioral Response Function with the 50 percent credible interval shaded in teal.

3.1.8.4 Mysticetes

All data used to develop the Phase 4 mysticete behavioral response function were from field research exposing whales to sonar or sonar-like signals (Table 24: Mysticete data relied upon for quantitative assessment of behavioral response.). Fin and blue whales in these behavioral response studies often responded at lower received levels (< 120 dB re 1 μPa) or did not respond at any received level. This was likely due to the number of context-based variables inherent in these studies; there was often more than one vessel present, the vessel(s) were often close (within 1-3 km) to the focal whales, and those whales that did respond (e.g., the blue whales from the SOCAL BRS) were typically engaged in more "sensitive" behaviors – deep foraging dives in the case of the blue whales (Goldbogen et al., 2013). The whales that were exposed to real Navy sonar from greater distances did not respond at all. Additionally, the fact that few humpback whales responded and all at moderate received levels and close ranges is indicative of the contextually- and species-dependent nature of their behavioral responses as well (e.g., some responses during foraging, no significant responses on breeding grounds). In contrast, the two minke whales both exhibited strong responses but also at moderately high levels. Therefore, while there are context-based responses there may also be some species with heightened sensitivity overall that are likely to respond no matter what the context, and others with low sensitivity that respond infrequently. Mysticetes in these behavioral response studies were exposed to levels from 85 – 182 dB re 1 μPa, and overall response levels ranged from 105 to 165 dB re 1 μPa with a mean response level of 130 dB re 1 μPa. However, because most exposures and responses occurred at lower received levels, the estimated probability of response increased steeply between this level and 200 dB re 1 μPa at which all animals were assumed to respond (Figure 41). The resulting curve has a 50 percent probability of response at 185 dB re 1 μPa.

Table 24. Mysticete data for quantitative assessment of behavioral response.

Species	Study	Individuals	Exposures	Range of Exposure Received Levels (dB re 1 µPa)	Significant Responses	Range of Response Received Levels (dB re 1 µPa)	Distances of Responses (km)
Blue Whale	SOCAL BRS (Goldbogen et al., 2013; Southall et al. 2019b)	16	28	94 – 165	4	105 –143	0.8 – 8.1
Blue Whale	LFA Playbacks (Clark et al., 1999)	1	1	95 – 150	0	NA	NA
Fin Whale	SOCAL BRS (Southall et al. 2023)	13	13	110 – 161	0	NA	NA
Fin Whale	LFA Playbacks (Clark et al., 1999)	6	6	115 – 155	0	NA	NA
Minke Whale	SOCAL BRS Kvadsheim et al. 2017	1	1	100 – 160	1	146	1
Humpback Whale	3S (Sivle et al., 2015)	10	20	85 – 182	4	125 – 165	0.1 – 0.4
Minke Whale	3S (Sivle et al., 2015)	1	1	83 – 158	1	146	4.5
Humpback Whale	LFA Playbacks (Miller et al., 2000)	17	17	121 – 150	0	NA	NA

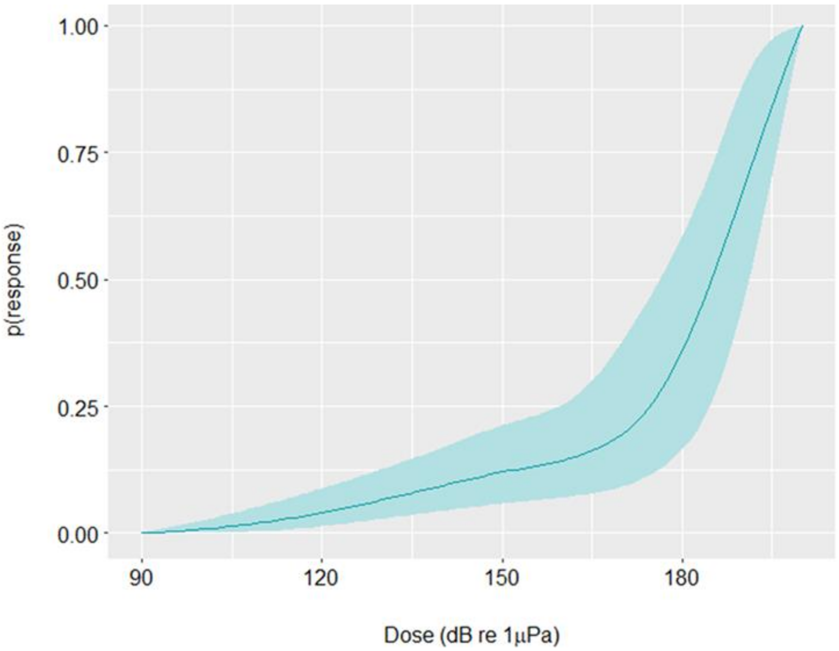


Figure 41. Mysticete Biphasic Behavioral Response Function, with the 50 percent credible interval shaded in teal.

3.1.8.5 Sirenians (Manatees and Dugongs)

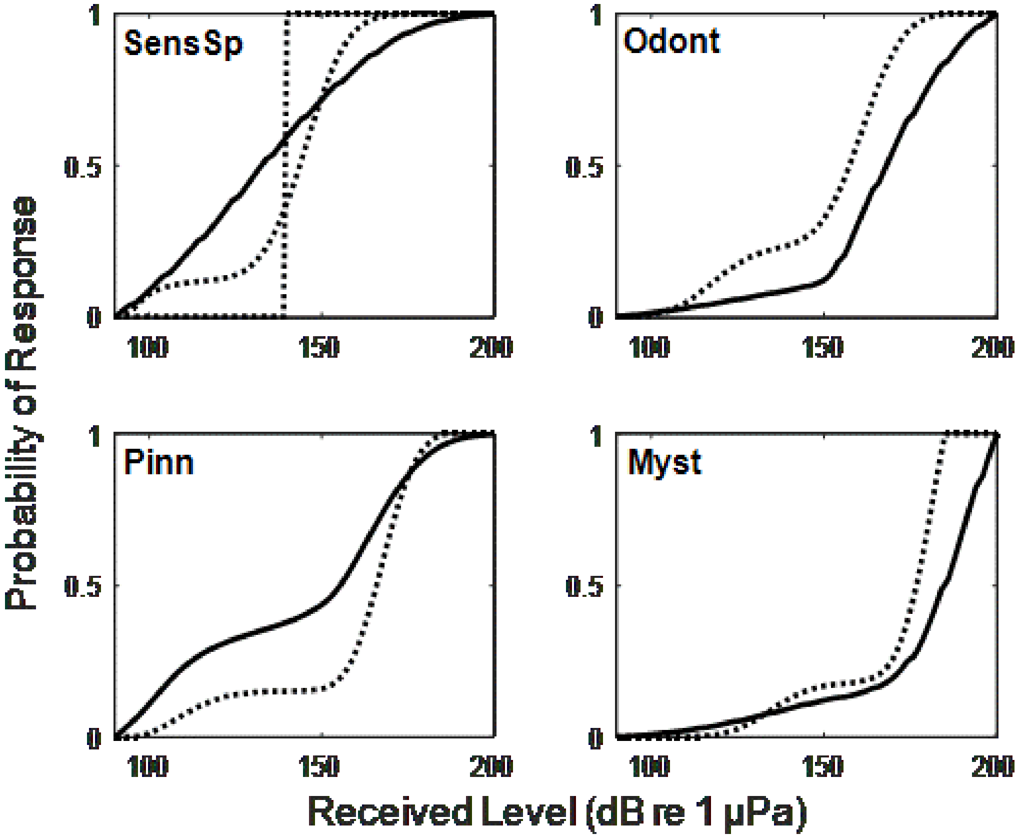
Due to a lack of specific data regarding sirenian reactions to sonar and sonar-like signals, the mysticete criteria and thresholds are considered the best proxy, as both mysticetes and manatees have demonstrated similar reactions to vessel noise.

3.1.8.6 Sea Otters and Polar Bears

Due to a lack of specific data regarding sea otter or polar bear reactions to sonar and sonar-like signals, the pinniped criteria and thresholds are considered the best proxy. Pinnipeds are the most closely taxonomically-related marine mammal group and share amphibious characteristics with polar bears and otters.

3.1.8.7 Comparison of Phase 3 and Phase 4 Behavioral Response Functions

Figure 42 shows the differences between the behavioral response functions used in Phase 3 versus those that are discussed in this report for Phase 4.



SensSp =Sensitive Species
Odont = Odontocetes
Pinn = Pinnipeds
Myst = Mysticetes
The Phase 3 beaked whale response function and the harbor porpoise step function are plotted against the Sensitive Species curve.

Figure 42. Behavioral Response Functions from Phase 3 (dashed lines) and Phase 4 (solid lines).

3.1.9 Behavioral Cutoff Conditions

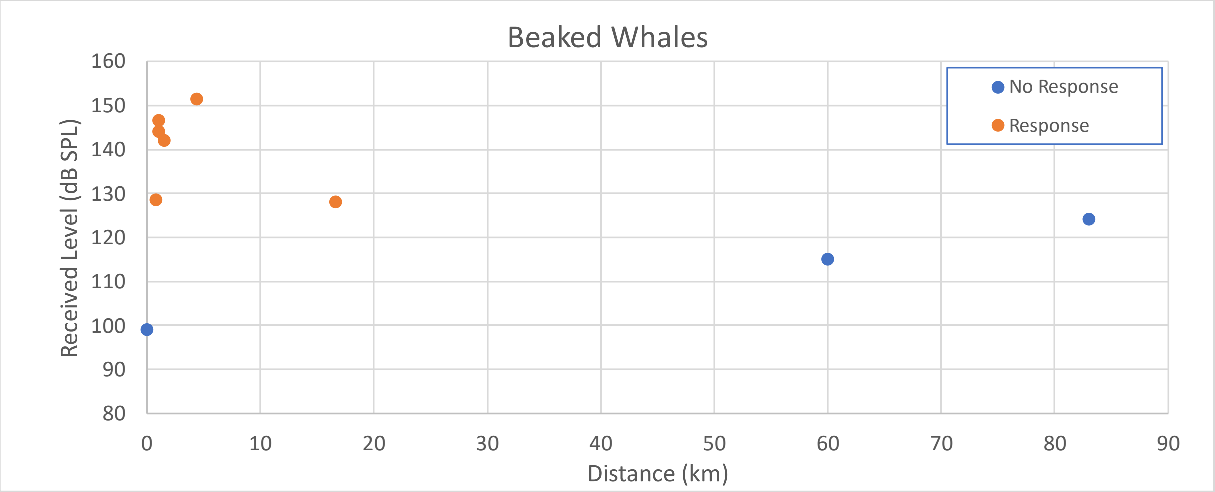
As discussed above in 3.1.2, at moderate to low received levels the correlation between probability of reaction and received level is very poor and it appears that other variables mediate behavioral reactions (e.g., Ellison et al., 2011) such as the distance between the animal and the sound source. For the Phase 4 analysis, distance between the animal and the sound source (i.e., range) was initially included as a potential covariate in the updated Bayesian risk function models. However, the models did not select range as a factor in the final risk function as it was too confounded with received level and therefore did not provide additional information about the possibility of response. This is not surprising given that only 21 of 196 exposures within the behavioral response data occur at 10 km or greater from the sound source. Of those 21 animals, 19 had no response at all, one had a minor vocal response, and one had a strong avoidance response that lasted less than the duration of the exposure.

These data provide support that beyond a certain distance, significant behavioral responses are unlikely to occur. However, at ranges less than 10 km there are several responses at received levels below 140 dB re1 μPa, which supports the idea that proximity can lead to reactions even at lower received levels. Since most data used to derive the behavioral response functions is from within 10 km of the source, probability of reaction at farther ranges is not well-represented. Therefore, the source-receiver range must be included as a separate consideration to estimate likely significant behavioral reactions. The Navy will use behavioral cutoff conditions where an animal beyond a certain distance and below a specific received level is unlikely to incur a significant behavioral response.

The cutoff distance will generally be based on the farthest source-animal distance across all known studies where animals exhibited a significant behavioral response. Animals beyond the cutoff distance but receiving levels above the 50 percent probability of response from that species' respective BRF, will also be assumed to incur a significant behavioral response. The probability of significant behavioral reactions occurring under these circumstances is unknown based on best available science, so this is being included as a conservative assumption due to the paucity of data. In both the case of animals being within the cutoff distance, and beyond the cutoff distance but still above the 50 percent probability of response for that species, a behavioral response function based on a received SPL as presented in 3.1.8 is used to predict the probability of a significant behavioral response.

3.1.9.1 Sensitive Species

As seen in Figure 43, there were nine instances from the data used to derive the behavioral response functions where the received level, source-animal distance, and animal's response were known. All exposures were to beaked whales. Significant behavioral reactions were not observed beyond about 17 kilometers, although there were no observations in this dataset between about 17 and 60 km.



Beaked whale exposures to sonar or simulated sonar ($n = 9$) comparing received level (dB re $1\mu\text{Pa}$) to distance from data used to derive the behavioral response functions where distance was also accurately recorded.

For exposures that caused a reaction, the distance and received level are those at which the reaction occurred.

For exposures that did not cause a significant behavioral reaction, the minimum distance and maximum received level are shown.

Figure 43. Beaked whale exposures to sonar or simulated sonar.

There are several other studies where animals were tracked using passive acoustic methods or satellite tracking tags. Although the received sound level, source-animal distance, and animal’s reaction are more difficult to discern than the data that was incorporated into the BRFs, these studies do provide more information about reactions at farther ranges.

During a Navy training event at Atlantic Underwater Test and Evaluation Center (AUTEC) in Andros Bahamas, Blainville's beaked whales moved an average of 16 km from the sonar transmissions (Tyack et al., 2011). During playback experiments of simulated sonar off the coast of SOCAL, sonar exercises approximately 118 km range from exposed whales with SPLs at the whales of 78 to 106 dB re 1 µPa did not elicit significant behavioral reactions (DeRuiter et al., 2013). Likewise, in observations during the SOCAL behavioral response study, beaked whales showed no observable response to hull-mounted ASW sonar at distances of 60 to 75 km (Southall et al., 2014; Southall et al., 2016). Recent analyses of possible Blainville's beaked whale behavioral responses to Navy sonar at the Pacific Missile Range Facility found cessation of clicks to occur when ships were between 10 to 35 km and typically approaching the location of the group. Groups continued to click when ships were between 25 and 40 km and typically heading away from the location of the group (Henderson et al., 2016). In Joyce et al. (2020), Blainville's beaked whales were satellite tagged on or near the AUTEC range in the Bahamas and then tracked before, during, and after sonar activity on the range. Exact distances to the location of the sonar were not given, but the whales were 2 – 27 km from the range when they responded by moving away from the range, while an animal 73 km from the range moved towards it. Even a study of northern bottlenose whales in a habitat with low ambient noise levels and little sonar use (Wensveen et al. 2019) found that behavioral responses occurred out to about 27 km in satellite tagged whales, but did not occur in a whale at about 36 km. Finally, while it has been shown that beaked whales reduce their foraging activity while on Navy ranges during Navy activities that include sonar (Moretti et al. 2014; Jacobson et al. 2022), two Blainville's beaked whales that were tagged on the PMRF range remained on or near the range during multiple days of sonar use (Baird et al. 2021).

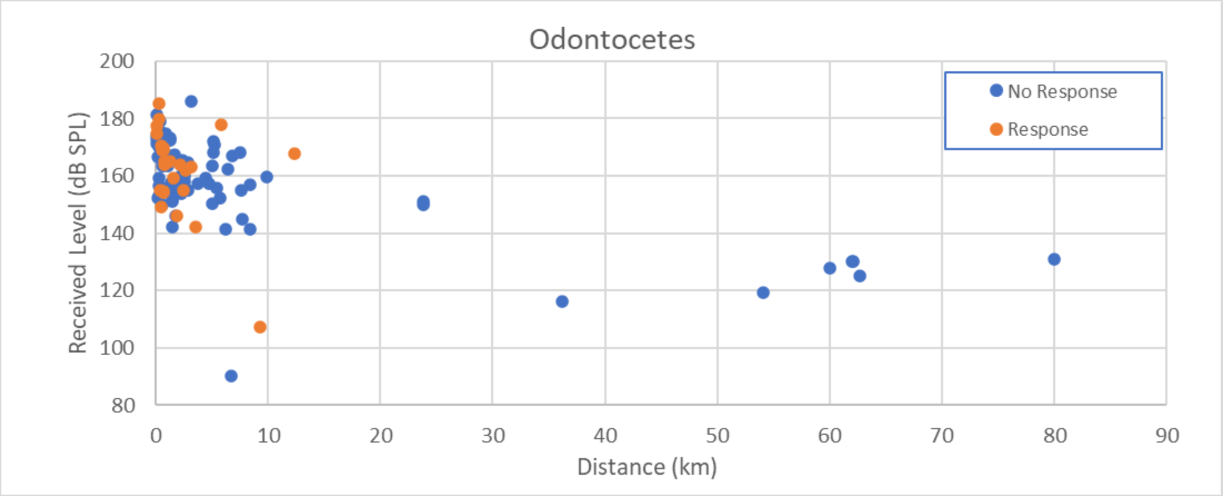
Although none of the studies above observed reactions in beaked whales to sources beyond about 35 km, Falcone et al. (2017) modeled apparent responses to mid-powered sources out to 50 km and responses to high-powered sources at distances as great as 100 km. However, the models were not developed to estimate distances to response, and care needs to be taken when interpreting the results in that context. Furthermore, most modeled responses occurred within 50 km.

There are no data available on the reaction distances of wild harbor porpoises to sonar or sonar-like signals. However, movement patterns of harbor porpoises have been studied during pile driving to install wind turbines in European waters (Dähne et al., 2013, 2014; Tougaard et al., 2009). These studies have shown that harbor porpoises are displaced to within about 20-25 km of the activity area.

The data suggest that most beaked whales and harbor porpoises are unlikely to exhibit significant behavioral reactions to high-powered sonar and sonar-like signals beyond approximately 35 km; therefore, the Navy will use 40 km as a cutoff distance for sensitive species. Based on the sound source and modeled sound propagation under certain environmental conditions, areas beyond 35 km can still be exposed to levels above the 50 percent probability of response on the sensitive species BRF which is 133 dB re 1 µPa. Therefore, animals within the sensitive species behavioral group that are beyond 40 km from the source and below 133 dB re 1 µPa are unlikely to incur significant behavioral reactions.

3.1.9.2 Odontocetes

As seen in Figure 44, there were 101 instances from the data used to derive the behavioral response functions where the received level, source-animal distance, and animal's response were known. All exposures were to Risso's dolphins, pilot whales, sperm whales, and killer whales. The 3S and BRS sonar playback studies were largely conducted within about 8 km, so it is difficult to extrapolate to the distance at which other odontocetes are not likely to respond, although significant behavioral reactions were not observed beyond about 12 kilometers. During the final SOCAL BRS field seasons, researchers were able to coordinate with Navy ships to expose two tagged Risso's dolphins (*Grampus griseus*) to actual mid-frequency sonar. These distances were on the order of tens of kilometers, and no responses were observed (Southall et al., 2014).



Odontocete exposures to sonar or simulated sonar ($n = 101$) comparing received level to distance from data used to derive the behavioral response functions where distance was also accurately recorded.

For exposures that caused a reaction, the distance and received level are those at which the reaction occurred.

For exposures that did not cause a significant behavioral reaction, the minimum distance and maximum received level are shown.

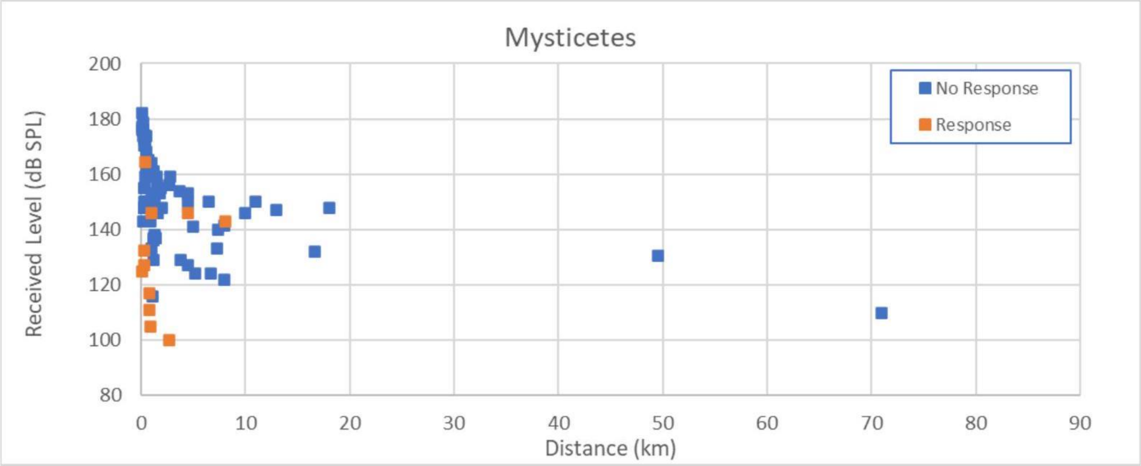
Figure 44. Odontocete exposures to sonar or simulated sonar.

In addition to the distance and response data from all CEEs, the determination of cut-off distances relied upon the 3S3 sperm whale data from 2019 in which animals responded out to 12.3 km. The relationship between range and received level were statistically analyzed using three different approaches. First, a Generalized Additive Mixed Model (GAMM) was developed with a variety of covariates to predict the likelihood of a “non-foraging active state” (NFA), which is a behavioral state that was only observed during a behavioral response. It was determined that the SEL max (per session), minimum distance (per session), and an interaction term between the two variables (as well as the presence of blackfish and a time-of-day variable) were the significant covariates selected in the model for that specific response. NFA was found to significantly increase over baseline during exposures with higher SEL values and closer ranges (over 120 dB SEL and less than 12 km), but beyond 20 km there was a low likelihood of that behavior and only at high SEL values (Lam et al. 2021). Second, a Generalized Estimating Equation (GEE) model was developed that incorporated all possible response categories for each session (e.g., avoidance, orientation, diving, foraging, vocal behavior, etc.), and then scored the total number of responses over all possible categories. This score was then modeled against several variables and once again the maximum SEL (per session), the minimum range (per session), and their interaction term were selected as significant. The conclusion from this analysis was that range drives the proportion and severity of the response, such that a higher proportion of responses per session occurred at closer ranges (Lam et al. 2021). Third, a two-stressor dose response function was fitted to data that included the maximum SEL and minimum distance prior to the onset of the response, or the maximum SEL and minimum distance in the session if there was no response. In the two-stressor dose response model, moderate and high severity responses were again predicted out to about 12 km (Wensveen et al. 2022). The two-dimensional response relationship of range and received level were compared to the one-dimensional response relationship of received level only, and it was found that the inclusion of range reduces animal disturbance at longer distances (von Benda Beckman and Wensveen 2022). These three analyses of the sperm whale data all demonstrate the importance of range as well as received level at close distances, but also provide good support that at longer distances significant behavioral responses are unlikely.

The data suggest that odontocetes (excluding beaked whales and harbor porpoises) are unlikely to exhibit significant behavioral reactions to high-powered sonar and sonar-like signals beyond approximately 12 km; therefore, the Navy will use 15 km as a cutoff distance for odontocetes. Based on the sound source and modeled sound propagation under certain environmental conditions, areas beyond 15 km can still be exposed to levels above the 50 percent probability of response on the odontocete BRF which is 168 dB re 1 µPa RMS. Therefore, animals within the odontocete behavioral group that are beyond 15 km from the source and below 168 dB re 1 µPa are unlikely to incur significant behavioral reactions.

3.1.9.3 Mysticetes

As seen in Figure 45, there were 85 instances from the data used to derive the behavioral response functions where the received level, source-animal distance, and animal's response were known. All exposures were to minke whales, fin whales, humpback whales, and blue whales. Significant behavioral reactions were not observed beyond about 8 kilometers.



Mysticete exposures to sonar or simulated sonar ($n = 85$) comparing received level (dB re $1\mu\text{Pa}$) to distance from data used to derive the behavioral response functions where distance was also accurately recorded.

For exposures that caused a reaction, the distance and received level are those at which the reaction occurred.

For exposures that did not cause a significant behavioral reaction, the minimum distance and maximum received level are shown.

Figure 45. Mysticete exposures to sonar or simulated sonar.

Data from the SOCAL BRS study on blue and fin whales included exposures to both simulated sonar within a few kilometers and sonar from real Navy ships at greater distances (tens of kilometers). None of the fin whales responded, while four of the blue whales responded. Three blue whales responded to the simulated sonar within 1 km, while one blue whale responded to real Navy sonar at 8.1 km (Goldbogen et al. 2013; Southall et al. 2019b). During Phase I of LFA playbacks, no responses by either blue or fin whales were observed; in one case a whale swam past the transmitting vessel in the direct path of the playback at a range of 200 - 300 m. During Phase 2 of LFA playbacks, migrating gray whales avoided the source by 500 - 2000 m when it was placed near the center of their migratory path; however, when the source was moved approximately 2 km farther offshore, the animals no longer altered their paths (Buck & Tyack, 2000; Clark et al., 1999; Ellison et al., 2011). In addition, the Behavioural Response of Australian Humpback whales to Seismic Surveys (BRAHSS) study was a CEE conducted to assess behavioral responses of migrating humpback whales to seismic airguns (Dunlop et al. 2013, 2016, 2017). Responses were found to be more likely when the source was within 3 km or above 140 dB re 1 µPa, although responses were variable (Dunlop et al. 2017). Similarly, Frankel and Stein (2020) observed changes in migration behavior of gray whales exposed to a high frequency 25 kHz source. While the whales were observed over 8 km (4 km north of the source to 4 km south of the source) significant changes in movement behavior and distance to shore were only observed up to 1 km from the source.

In contrast, acoustically-tracked minke whales at PMRF in Hawaii, likely on their breeding grounds, avoid the main area of MFAS training activity on the range, moving north or west away from the activity at higher travel speeds (Harris et al. 2019; Durbach et al. 2021). Avoidance distances were not explicitly measured but estimates of the locations of tracks compared to the center of activity indicates that minke whales may avoid sonar at 20 – 50 km during Navy activities that have multiple high-powered sound sources. However, it cannot be determined if the whales physically avoided the area or simply ceased vocalizing.

It is important to note that these are the distances within which behavioral responses have been observed, which is decoupled from the acoustic habitat or communication space that these large whales likely utilize. While their low frequency vocalizations may be detected across tens to hundreds of kilometers, their observed behavioral responses to low- and mid-frequency active sonar seem to be limited to within 10 km.

The data suggest that most mysticetes are unlikely to exhibit significant behavioral reactions to high-powered sonar and sonar-like signals beyond approximately 8 km; therefore, the Navy will use 10 km as a cutoff distance for mysticetes. Based on the sound source and modeled sound propagation under certain environmental conditions, areas beyond 10 km can still be exposed to levels above the 50 percent probability of response on the mysticete BRF which is 185 dB re 1 µPa. Therefore, animals within the mysticete behavioral group that are beyond 10 km from the source and below 185 dB re 1 µPa are unlikely to incur significant behavioral reactions.

3.1.9.4 Pinnipeds

All studies of pinniped behavioral responses utilized in the Phase 4 risk functions were from captive studies conducted at close range. Southall et al. (2007) report that pinnipeds do not exhibit strong reactions to SPLs up to 140 dB re 1 µPa from steady state (non-impulsive) sources. In some cases, pinnipeds tolerate impulsive exposures up to 180 dB re 1 µPa with limited avoidance noted (Southall et al., 2007), and no avoidance noted at distances as close as 42 m (Jacobs & Terhune, 2002). There are limited data on pinniped behavioral responses beyond about 3 km in the water.

The data suggest that most pinnipeds are unlikely to exhibit significant behavioral reactions to high-powered sonar and sonar-like signals beyond approximately 3 km; therefore, the Navy will use 5 km as a cutoff distance for pinniped. Based on the sound source and modeled sound propagation under certain environmental conditions, areas beyond 5 km can still be exposed to levels above the 50 percent probability of response on the pinniped BRF which is 156 dB re 1 µPa. Therefore, animals within the pinniped behavioral group that are beyond 5 km from the source and below 156 dB re 1 µPa are unlikely to incur significant behavioral reactions.

3.2 IMPULSIVE SOUND SOURCES

3.2.1 Introduction

This section outlines the criteria used in Navy Phase 4 analysis to predict behavioral effects to marine mammals from impulsive sound sources, including pile driving, air guns, and explosives. Impulsive signals, particularly at close range, have a rapid rise time and higher instantaneous peak pressure than other signal types, making them more likely to cause startle responses or avoidance responses. However, at long distances the rise time increases as the signal duration lengthens (similar to a "ringing" sound), making the impulsive signal more similar to a non-impulsive signal (Hastie et al., 2019; Martin et al., 2020). Behavioral reactions from explosive sounds are likely to be like reactions studied for other impulsive sounds, such as those produced by air guns and impact pile driving. Data on behavioral responses to impulsive sound sources are limited across all marine mammal groups, with only a few studies available for mysticetes and odontocetes. Most data have come from seismic surveys that occur over long durations (e.g., on the order of days to weeks), and typically utilize large multi-air gun arrays that fire repeatedly, or from acoustic studies of pile driving activity that can detect a change in distribution of animals over time. While seismic and pile driving data provide the best available science for assessing behavioral responses to impulsive sounds by marine mammals, it is likely that these responses represent a worst-case scenario compared to responses to explosives used in Navy activities, which would typically consist of single impulses or a cluster of impulses (i.e., acute sounds), rather than long-duration, repeated impulses (i.e., potentially chronic sounds).

Compared to sonar, there are few direct observations of behavioral reactions from marine mammals due to exposure to impulsive sounds. Like the behavioral response criteria for sonar and sonar-like signals, to contribute to marine mammal impulsive behavioral response criteria and thresholds, data had to include (1) an observation or description of behavioral response (or demonstrated that there was no response) to an impulsive sound source, and (2) report a received level metric. Studies omitting either one of these inclusion criteria were not included in the body of this literature review. This data could eventually be used in the development of a future impulsive behavioral response risk function when there is additional data to support that effort. These studies are shown in Appendix F.

3.2.2 Behavioral Response Thresholds for Air Guns

Existing National Marine Fisheries Service risk criteria are applied to the unique sounds generated by air guns at 160 dB re 1 µPa. The rms calculation for airguns is based on the duration defined by 90 percent of the cumulative energy in the impulse. There have been many studies conducted on behavioral responses of marine mammals to air guns and seismic surveys; however, the majority of these have been opportunistic, and do not report received levels along with specific behavioral responses. However, the most pertinent studies have been summarized below.

3.2.2.1 Opportunistic Behavioral Response Studies of Seismic Surveys

Koski and Johnson (1987) observed a mother and calf bowhead whale feeding at the onset of seismic activity 17 km away with an estimated RL of 126 dB re 1 µPa. No behavioral responses were observed, although after 30 min the pair swam away at a moderate speed. These authors also observed another group of bowhead whales 24 km from a seismic ship that had shorter dives, longer periods at the surface, and more blows during seismic activity than for other migrating whales; this response occurred at estimated levels of 117 – 137 dB re 1 µPa. Ljungblad et al. (1988) also observed bowhead whales near seismic activity, and found short-term behavioral changes when animals were less than 10 km from the vessel, including tail slapping, startle responses, and avoidance behavior. These responses occurred at received levels of 142 – 178 dB re 1 µPa. Similarly, Miller et al. (2005) found bowhead whales had reduced sighting rates on feeding grounds during seismic activity and increased sighting distances from the vessel and interpreted this as local avoidance of the source at an estimated received level of about 170 dB re 1 µPa. However, during aerial surveys in the same study, avoidance was not observed, and bowhead whales were sighted 5.3 – 20 km from seismic activity, with estimated received levels of 130 – 150 dB re 1 µPa. Richardson et al. (1999) found avoidance by bowhead whales out to 20 – 30 km from the seismic vessel; estimated received levels at 20 km were 120 – 135 dB re 1 µPa when propagation was favorable, and 116 – 117 dB re 1 µPa under more typical propagation conditions.

Humpback whales were also observed avoiding seismic survey activity at ranges of 5 – 8 km, although some individual adult males approached the source at estimated maximum received levels of 179 dB re 1 µPa (McCauley et al. 2000a). The most common avoidance behavior was to alter the speed or direction of travel to maintain a standoff distance of about 3 – 4 km from the vessel, at estimated received levels of 157 – 164 dB re 1 µPa.

Sperm whales were monitored during exposure to distant (4—86 km away) seismic activity in Norway, at maximum estimated received levels of 130 dB re 1 µPa with no observed avoidance or displacement behavior or change in vocal activity during foraging behavior (Madsen et al. 2002).

Ringed seals were also monitored during seismic surveys in Alaska (Harris et al. 2001); sighting rates were similar between seismic and non-seismic periods, and while the seals may have avoided the seismic vessel within 150 m and more seals swam away when air guns were active, they were still found within 250 m and did not leave the general area. Received levels were estimated to be greater than 180 dB re 1 µPa out to 1 km from the vessel, and were 190 – 195 dB re 1 µPa within 150 – 250 km.

Gray whales on feeding grounds off Sakhalin Island were observed before, during, and after seismic surveys (Gailey et al. 2016), and individual animal behaviors were described along with the development of models looking at what might drive behavioral changes. The models did not find a strong relationship between the behavior of the whales and the seismic activity overall; however, a few individuals were observed to respond. One animal fast traveled towards the area of seismic activity before turning inshore and away from the seismic activity; during the period of approach the received levels increased from 143 to 151 dB re 1 $µPa^2s$ SEL. Another animal changed direction of travel toward the seismic activity and increased travel speed at the onset of seismic activity, at received levels of about 127 to 139 dB re 1 $µPa^2s$ SEL.

These data could eventually be used in the development of a future impulsive behavioral response risk function when there is sufficient data to support that effort.

3.2.2.2 Passive Acoustic Monitoring During Seismic Activity

Multiple studies have purposely or opportunistically recorded vocal activity of marine mammals during seismic activity. Blue and fin whales were acoustically tracked during exposures to air guns in the North Pacific Ocean; one whale that may have been actively approaching the seismic vessel called at 15 km distance but stopped calling at 10 km where levels were estimated to be about 127 dB re 1 µPa. Similarly, blue whales in the St. Lawrence Estuary were recorded during periodic sparker activity (Di Iorio and Clark 2009). These whales were found to vocalize more on days with activity and may have been vocally compensating for the elevated ambient noise levels. The mean estimated SPL in the area at the time was about 123 dB re 1 µPa. Dunn and Hernandez (2009) also tracked blue whales during a period of seismic activity at received levels less than 145 dB re 1 µPa and distances greater than 15 km with no observed change in heading or speed.

Bowhead whales were acoustically monitored in the Beaufort Sea during their migration and call rates were compared before, during, and after periods of seismic activity (Blackwell et al. 2013). Fewer calls were detected from animals "near" the activity (41-45 km) than animals "distant" to the activity (>104 km); median levels at the "near" locations were 116 – 129 dB re 1 µPa while the more "distant" levels were 99 – 108 dB re 1 µPa. Furthermore, call rates were initially found to increase at the onset of air gun pulses at cSEL values of 94 dB re 1 µPa^{2}s, then started decreasing at 127 dB re 1 µPa^{2}s cSEL and stopped after levels exceeded 160 dB re 1 µPa^{2}s cSEL (Blackwell et al. 2015), indicating different types of acoustic behavioral responses at different received levels.

Harbor porpoise vocalizations were detected using C-Pods (cetacean and porpoise detector) placed at various distances from seismic activity, up to 15 km away (Sarnocińska et al. 2020), and detections were compared for periods before, during, and after seismic activity. The lowest amount of vocal activity was detected at the sites closest to the seismic vessel at single shot SEL values of about 155 dB re 1 µPa^{2}s, and activity levels increased with distance from the vessel, with vocalizations at 15 km like baseline levels.

Since a change in vocal activity without an associated visual observation does not fully inform the type of behavioral response that may have occurred, and since received levels were estimated for general areas but not specific animal locations, these data cannot be used in the development of a behavioral risk function for impulsive sound sources.

3.2.2.3 Controlled Exposure Field Studies Using Seismic Airguns

In some of the earliest controlled exposure field studies, Malme et al. (1984, 1985, 1988) exposed gray and humpback whales to seismic arrays (or playbacks) during both migration and feeding activity. During migration, gray whales changed course to avoid the sound source placed in their path out to distances of 3 km; the avoidance threshold of a single air gun was estimated to be 164 dB re 1 µPa, while the overall 50 percent avoidance threshold was estimated to be 170 dB re 1 µPa. During feeding behavior, cessation of feeding was observed on some occasions, along with changes in direction or speed of movement, at received levels of 149 – 176 dB re 1 µPa and distances up to 4 km. While most gray whales returned to the area and resumed feeding once the air gun was stopped, one whale exposed at 154.5 dB re 1 µPa continued moving out of the area. However, in another instance levels reached 165 dB re 1 µPa with no response observed, and some whales remained feeding up to received levels of 176 dB re 1 µPa. In this study, Malme et al. (1988) estimated the 50 percent probability of an avoidance/cessation of feeding response by gray whales to be 173 dB re 1 µPa. For foraging or resting humpback whales, no clear avoidance behavior was observed at received levels up to 170 dB re 1 µPa (Malme et al. 1985), although there was some startle behavior when the air gun was first turned on.

McCauley et al. (2000a) also conducted controlled air gun exposures to migrating humpback whales with a single air gun. Avoidance behavior was observed from 1.22 to 4.4 km (the vessel was not allowed to get closer to the animals); whales at 5 km were not observed to change their behavior. Avoidance occurred at about 140 dB re 1 µPa, with the 1.3 km distance at 143 dB re 1 µPa and startle responses at 112 dB re 1 µPa. Resting animals were more sensitive and avoided at greater ranges, out to 7 – 12 km, which also corresponded to received levels of about 140 dB re 1 µPa.

More recently, the BRAHSS study was conducted to assess behavioral responses of migrating humpback whales to seismic air guns in a controlled exposure study format. Dunlop et al. (2013, 2016, 2017) towed both single and arrays of air guns across the migratory path of humpback whales with and without ramp up. They also used controls, with the air guns towed but not active, to assess the impact of just the survey vessel. When comparing received levels and behavioral responses using ramp-up versus a constant noise level of air guns, humpback whales did not change their dive behavior but did deviate from their predicted heading and decreased their swim speeds (Dunlop et al., 2016). When looking at the relationships between proximity, received level, and behavioral response, Dunlop et al. (2017) used responses to two different air guns and found responses occurred more toward the smaller, closer source than to the larger source at the same received level, demonstrating the importance of proximity. Responses were found to be more likely when the source was within 3 km or above 140 dB re 1 µPa, although responses were variable, and some animals did not respond at those values while others responded below them. In addition, responses were generally small, short-term course deviations of only around 500 m (Dunlop et al. 2017).

Richardson et al. (1985, 1986) also conducted controlled exposures of a single air gun to bowhead whales, along with exposures to more distant seismic activity. There were no detected responses to the distant surveys at received levels of 107 – 158 dB re 1 µPa. During the controlled exposures, the whales began orienting away from the source at about 7.5 km, although some continued feeding until the vessel was 3 km away. All whales avoided the source at 2 km distance, with minimum received levels of at least 134 dB re 1 µPa. When a playback study was conducted, normal behavior was observed at distances of 3 – 5 km and received levels of 118 – 133 dB re 1 µPa. In two cases, whales traveled away at medium-fast speeds at received levels of 124 - 134 dB re 1 µPa and ranges of 0.2 to 4.5 km.

A controlled exposure study of air gun arrays was also conducted with sperm whales tagged with acoustic DTAGs (Miller et al. 2009, Madsen et al. 2006). With exposures up to 162 dB re 1 µPa at distances of 1.4 – 12.8 km away, all whales but one continued to conduct normal foraging dives and demonstrated no avoidance behavior, although tag data may have suggested subtle changes in feeding behavior. One whale that had been resting at the surface at the start of the experiment remained at the surface for the duration of the exposure and only then conducted a foraging dive, which could be a delay in foraging. This whale also had the closest approach and highest exposure level.

These data (Table 25) could eventually be used in the development of a future impulsive behavioral response risk function when there is sufficient data to support that effort.

Table 25. Summary of received levels and distances for marine mammal behavioral responses to seismic air guns in field studies.

Species	RL range at Response (SPL dB rms)	Distance range at Response (km)	Type of study
Bowhead whale [1–7]	117 - 170	2 - 45	boat and aerial surveys
Gray whale [8–11]	127 - 173	3 - 4	boat and shore-based surveys
Humpback whale [9,12–14]	140 - 179	1.2 - 8	boat and shore-based surveys
Sperm whale [15–17]	NA (130 – 162)	NA (4 – 86)	boat survey
Blue whale [18–19]	123 - 127	10	boat survey
Harbor porpoise [20]	155 (SEL)	15	boat survey
Phocid seals [21]	195	0.15	boat survey

[1] Koski and Johnson (1987); [2] Ljungblad et al. (1988); [3] Miller et al. (2005); [4] Richardson et al. (1999); [5] Blackwell et al. (2013); [6–7] Richardson et al. (1985, 1986); [8–10] Malme et al. (1984; 1985; 1988); [11] Gailey et al. (2016);

[12] McCauley et al. (2000a); [13–14] Dunlop et al. (2013, 2016, 2017); [15] Madsen et al. 2002; [16] Miller et al. 2009;

[17] Madsen et al. (2006); [18] Di Iorio and Clark (2009); [19] Dunn and Hernandez (2009); [20] Sarnocińska et al. (2020);

[21] Harris et al. 2001

3.2.2.4 Captive Animal Controlled Exposure Studies Using Seismic Air Guns

A few studies have also exposed captive animals to seismic air guns (or playbacks) either to explicitly observe the behavioral response or opportunistically as a side effect. For example, Finneran et al. (2002) conducted a TTS study on a bottlenose dolphin and a beluga whale, and in both cases noted the animals were often reluctant to return to the biteplate following an exposure; for the beluga this occurred after the first exposure at 171 dB re 1 µPa, while for the bottlenose dolphin this behavior did not occur until a received level of almost 207 dB re 1 µPa. In a follow-on study, Finneran et al. (2015) exposed multiple bottlenose dolphins to air gun pulses, this time to measure hearing thresholds. Again, the dolphins did not exhibit any behavioral reactions at received levels of 170 – 187 dB re 1 µPa, and one did not change behavior at the highest level of 188 dB re 1 µPa. The other two dolphins began exhibiting anticipatory behavior, turning, or moving away from the sound source before the air gun pulse occurred and then returning to the biteplate afterward. Similarly, Finneran et al. (2003) exposed California sea lions to a pulsed arc-gap transducer (like an air gun). Mild behavioral responses in one animal began at a received level of 169 dB re 1 µPa, while at 165 dB re 1 µPa the other animal began evasive behavior such as lifting its head out of the water or hauling out.

Sills et al. (2020b) documented behavioral responses while studying the effect that single and multiple seismic air gun shots had on the hearing of one male bearded seal. For all three experiments, the seal only exhibited mild detectable responses for most exposures even up to single shot SELs of 185 dB re 1 µPa^{2}s, indicating that the seal did not move more than half his body, and always returned to continue participation.

Reichmuth et al. (2016) also exposed spotted and ringed seals to air guns to measure TTS, but opportunistically recorded behavioral responses as well. No behavioral responses were recorded in control trials, but all subjects exhibited mild behavioral responses during most exposure trials. These responses included moving the head from station or moving a short distance (less than half a body length or slightly more) from station but returning within the response window. These responses occurred at signal levels up to 206 dB re 1 µPa (peak to peak [pp]).

Lucke et al. (2009) exposed a harbor porpoise to air gun stimuli to measure TTS, up to received levels of 199.7 dB peak to peak (pp) re 1 µPa. Above 174 dB (pp) re 1 µPa the animal consistently demonstrated aversive behavior and avoidance of the pool area with the sound source.

All these studies exposed animals to very high received levels in close proximity with the purpose of stimulating a TTS response, therefore they would not be suitable to use in the derivation of a behavioral response function.

3.2.3 Behavioral Response Thresholds for Pile Driving

Existing NMFS risk criteria are applied to estimate behavioral effects from impact and vibratory pile driving (Table 26). The rms calculation for impact pile driving is based on the duration defined by 90 percent of the cumulative energy in the impulse.

Table 26. Pile Driving Level B Thresholds to Predict Behavioral Responses from Marine Mammals.

Underwater Vibratory Pile Driving Criteria Level B Disturbance Threshold	Underwater Impact Pile Driving Criteria Level B Disturbance Threshold
120 dB re 1 µPa rms	160 dB re 1 µPa rms

dB: decibel; dB re 1 µPa: decibel referenced to 1 micro pascal; rms: root mean square

Note: Root mean square for vibratory pile driving is calculated based on a representative time series long enough to capture the variation in levels—usually on the order of a few seconds.

While there is an increasing body of work examining behavioral responses to pile driving activity, as reviewed below, few studies record or report the information needed to derive a dose-response type metric. Therefore, the NMFS risk criteria will continue to be utilized in Phase 4.

3.2.3.1 Pile Driving During Wind Farm Construction

Several studies have been conducted to monitor marine mammals visually or acoustically, particularly harbor porpoises, during the construction of offshore wind farms; unfortunately, most of these studies only assessed behavioral and acoustic responses and did not report actual received levels. Pile driving for these wind farms can last for several weeks, and acoustic recorders have often been placed at multiple distances extending from the area of construction and then recorded for similar periods of time before, during, and after pile driving to determine the impact on marine mammals in the area. Received levels could be estimated or modeled for these studies, but for the most part, were not reported.

3.2.3.1.1 Harbor Porpoises

Several studies were conducted related to the construction of the Nysted offshore wind farm in the Baltic Sea (Henriksen et al. 2003; Tougaard et al. 2005; Carstensen et al. 2006). Three passive acoustic loggers, T-PODs, were deployed 2 – 4 km away from the foundation, with another set of three in a “reference” area 15 km away, and all recorded for an eight-month baseline period before construction as well as during the 18 months of construction. Harbor porpoise echolocation clicks would occur in bouts when porpoises were present in the area. There was an increase in between-bout periods during the construction phase from the baseline period; during the baseline period there were always less than 2 days (10–20 h) between bouts, but during construction click bouts were separated by up to a week (35–50 h), and once by 38 days. However, despite leaving the area when pile driving began, the animals always returned after each operation was finished (Tougaard et al. 2005).

Similar results were found for harbor porpoises exposed to impact pile driving outside the Moray Firth, Scotland (Thompson et al. 2010) and at the Horns Reef wind farm in the North Sea (Tougaard et al. 2003; Tougaard et al. 2009). Six T-PODS were deployed, three near the construction site and three at a control location 25 km away near the coast. These recorded for six months in 2006, for two months before, during, and after the pile driving activity, as well as for two months in the summers of 2005 and 2007 to compare numbers of detections over time. There were low levels of detections for bottlenose dolphins at both sites, and low levels of harbor porpoises at the control site, making comparisons between sites difficult. However, at the construction site significantly fewer harbor porpoise clicks were recorded (as hours per day) during the two months of construction than during the same two months in other years. During the pile driving activity, harbor porpoise behavior changed to more directional travel, and less “non-directional travel” (foraging) and logging. The daily intensity of clicks didn’t change from the baseline period to the construction phase, but the daily frequency of clicks decreased about 50 percent; however, this decrease could have also been attributable to interannual variation.

Brandt et al. (2011) also found similar responses by harbor porpoises in nearby Horns Reef II, a second wind farm developed in the North Sea. Noise measurements were made with an autonomous buoy about 720 m from the pile and from a ship-based hydrophone 2,300 m from the pile. Eight T-PODs were also deployed in a transect line running from 2.5 to 21.2 km from the construction zone. In one test, 449 blows were recorded over 30 min. At 720 m, the SPL was 196 dB re 1 µPa (pp), SEL (over 30 s) was 176 dB re 1 µPa^{2}s, and the M-weighted (weighted for harbor porpoise hearing) SEL was estimated at 170 dB re 1 µPa^{2}s. At 2,300 m, the SPL was 184 dB re 1 µPa (pp), SEL was 164 dB re 1 µPa^{2}s, and the M-weighted SEL was estimated at 157 dB re 1 µPa^{2}s. The acoustic activity of harbor porpoises was negatively affected out to 17.8 km; at the closest point (2.5 km), acoustic activity was reduced for 24 – 72 h after pile driving, and the duration of the effect declined with distance such that at 21.2 km there was no negative effect. In fact, at that range there was an increase in acoustic activity for about 30 h after pile driving, indicating the porpoises may have just moved further away from the noise during pile driving but were not otherwise impacted. Brandt et al. (2016) provided a summary report of harbor porpoise detections before, during, and after the construction of eight wind farms. They found that at noise levels above 170 dB re 1 µPa there was a 90 percent reduction in harbor porpoise detections, but at noise levels between 145 and 150 dB re 1 µPa there was only a 25 percent reduction. In a GAM model of distance as a proxy for noise levels, an effective range of 17 km was determined to be the distance out to which porpoises avoided pile driving at a significant level.

Dähne et al. (2013) monitored for harbor porpoises visually via aerial line transect surveys as well as acoustically using echolocation click loggers deployed from 1 to 50 km from the center of piling activity. From the aerial surveys they found a strong avoidance response out to 20 km, while the click detectors found a decrease in vocal activity only out to 10.8 km. They estimated that the SEL at 10 km would be about 146 – 152 dB re 1 µPa^{2}s.

The opposite effect was observed by Scheidat et al. (2011) at another wind farm, Egmond Aan Zee, in the Danish North Sea. Two T-PODs were deployed within the wind farm, over 260 m from the closest pile, with six additional T-PODs in two reference areas 10 km north and south of the wind farm. In this study, there were twice as many encounters, 72 percent longer durations of acoustic activity, and reduced waiting times (39 percent) during the operation than during the baseline period.

In addition, there were more clicks recorded, with longer encounter durations and less waiting time in the impact zone than in the reference areas. These effects were hypothetically attributed to an increase in food within the wind farm (a “reef effect”) or to an avoidance of disturbance by boats (a “shelter effect”) (Scheidat et al. 2011).

Due to the lack of reported estimated or measured received levels plus finite behavioral responses, none of these data can be used in the development of behavioral risk functions for impulsive sounds.

3.2.3.1.2 Other Odontocetes

Graham et al. (2017) used passive acoustic monitoring (PAM) devices to assess the activity and localize the occurrence of bottlenose dolphins over different area and time scales with and without impact pile driving. Noise recorders predicted the received broadband SEL 812 m from the piling site (133.4 dB re 1 µPa^{2}s). While there were fewer hours with bottlenose dolphin detections and reduced detection durations within the pile driving area and increased detection durations outside the area, the effect sizes were small. However, the comparatively small response in the species could be due to a substantially lower impact pile driving received level than reported in previous studies.

3.2.3.1.3 Pinnipeds

Edrén et al. (2010) and Teilmann et al. (2004) monitored seal behavior and abundance during the construction and operation of the Nysted offshore wind farm 4 km northeast of the Rodsand seal sanctuary, an important haul-out site for harbor seals (*Phoca vitulina*), and gray seals (Halichoerus grypus). Edrén et al. (2010) did not record sound levels but assumed source levels between 235 – 272 dB re 1 µPa at 1 m, taken from Tougaard et al. (2009) and others. The seal populations in this region had previously been reduced by 11 – 44 percent due to an epidemic of phocine distemper virus. By 2003 the population had recovered by about 19 percent, and throughout the construction and operation of the wind farm, the population continued to increase. Teilmann et al. (2004) reported no impact on the seal populations, with a positive change in numbers from the preconstruction to construction data. Edrén et al. (2010) reported lower numbers observed in June during construction than in the June of the year before or after construction, and lower numbers in the first September of operation than during construction. No sudden reactions were observed for either species when pile driving activities began. Finally, pile driving did lead to a decrease in the probability of seals on land when acoustic deterrents were used (20 – 60 percent reduction), but an increase in the probability of hauling out when acoustic deterrents were not used (25 percent increase). However, all responses were short-term, and were least noticeable during the molting season, when seals are strongly dependent on land.

Skeate et al. (2012) and Nedwell et al. (2003) estimated the impact of pile driving on harbor and gray seals near the Scroby Sands wind farm near Great Yarmouth, England. This wind farm was constructed near a sandbank that is a major haul-out site for both species of seal. Source levels were estimated at 257 dB (pp) re 1 µPa at 1 m and 202 dB (pp) re 1 µPa at 500 m, and transmission loss was estimated as TL = 20 log(D) – 0.003(D), where D is Distance (Skeate et al. 2012). The seasonal patterns of variation in abundance were consistent across years, with peaks for both species in late summer and fall, and minimum sighting levels in winter. However, harbor seal numbers were higher in the two years before construction, lowest during construction, and then climbed again after construction showing some recovery. In contrast, gray seal numbers were lowest before construction, and then highest during construction and remained high after construction, indicating that a shift in species composition occurred which may or may not have been related to the construction of the wind farm. Nedwell et al. (2003) also recorded noise measurements at the North Hoyle offshore wind farm, 7.5 km north of North Wales, in a water depth of 7 – 11 m.

There was an oil platform near this wind farm, with estimated source levels between 195.6 and 227.5 dB re 1 µPa at 1 m, which added to the background noise levels in the area. Sound pressure levels were recorded as 198 dB (pp) re 1 µPa at 955 m, 192 dB (pp) re 1 µPa at 1,881 m, and 184 dB (pp) re 1 µPa at 3,905 m.

Russell et al. (2016) compared the behavior of tagged harbor seals around an operational wind farm to that of a wind farm under construction and found the seals avoided the area of construction during pile driving out to about 25 km, with a reduction of usage within the area up to 83 percent at received levels between 166 and 178 dB (pp) re 1 µPa. This displacement only occurred during active piling activity, and within 2 hours the animals returned to the area. In the operational wind farm, there was an increase in animals using the area, possibly due to the aggregation of prey.

While these studies provided estimated source levels that could be used to estimate received levels, the reported behavioral responses are at the population level over long temporal scales and therefore cannot be used in the development of behavioral risk functions.

3.2.3.1.4 Pile Driving Exposures to Captive Animals

There were three harbor porpoises housed in an outdoor pool in a Danish harbor that were exposed to pile driving noise during construction across the harbor, at 100 – 175 m distance (Lucke et al. 2011). Pile driving activity occurred four days a week, with some longer breaks, over three months. When pile driving began, the porpoises demonstrated strong avoidance reactions, swimming to the far side of their enclosure rapidly, then logging at the surface for abnormally long periods. Over a piling sequence of 95 blows, levels varied from 168 – 181 dB (pp) re 1 µPa for SPL, and 137 – 149 dB re 1 µPa^{2}s for SEL. Piling activity was halted, and a bubble curtain was installed around the porpoise enclosure. There was a slight initial behavioral response to the bubble net as well, but then once pile driving resumed there were no further behavioral responses to the noise. Outside of the bubble net, the maximum SPL was 181 dB (pp) re 1 µPa, and SEL for a single blow was 149 dB re 1 µPa^{2}s, while inside the net, the maximum SPL was

166 dB (pp) re 1 µPa and SEL was 135 dB re 1 µPa^{2}s. This represents a mean 14 dB decrease in SPL and 13 dB decrease in SEL using the bubble curtain.

Kastelein et al. (2013c) exposed a harbor porpoise to playbacks of pile driving sounds from received levels of 130 to 154 dB in 6 dB steps. The porpoise did not avoid the transducer area at any of the received levels, but respiration rates increased at 136 dB re 1 µPa and above, and it began jumping at that level as well; although, the number of jumps was not significant until the 154 dB re 1 µPa received level was reached. Similarly, Kastelein et al. (2013d) exposed the same harbor porpoise to a general impulsive sound like the pile driving strike sound but with a much steeper rise time. During the 60- to 90-min sessions with 20 to 30 impulsive sounds played back, the harbor porpoise startled at each transmission with a strong tail swish, but then always returned to their baseline behavior and did not avoid the area around the transducer. They determined that the 50 percent level of these brief startle responses was at 92 dB re 1 µPa^{2}s SEL.

These studies report received levels and finite behavioral responses at the level of individual animals and could be used in the development of behavioral risk functions in the future when there are additional data as well.

3.2.3.1.5 Artic Oil Platform Construction

Two studies measured sound levels related to the construction and operation of Northstar Island, a man-made oil “island” in the Alaskan Beaufort Sea which is 9.5 km from land in 12 m deep water and is covered in land-fast ice from November through July (Moulton et al. 2003; Blackwell et al. 2004). Both studies also monitored the distribution patterns and behavior of ringed seals (*Phoca hispida*) related to the construction effort. Moulton et al. (2003) recorded maximum received levels of about 125 dB re 1 µPa at 350 m and 80 dB re 1 µPa at 5,000 m for vibratory pile driving, and 130 dB re 1 µPa at about 750 m and 108 dB re 1 µPa at 3 km for impact pile driving. Vibratory pile driving noise levels reached background levels at 2 – 4 km, while impact pile driving, with a pulse duration of 180 ms and repetition rate of 50 pulses per minute, had the highest noise levels of all the recorded sounds, reaching background levels at <5 km. The maximum energy of all recorded sounds, including pile driving, trenching, ice road construction, and trucks driving on the ice road, was below 100 Hz. Blackwell et al. (2004) recorded underwater sound pressure levels of pipe driving at 157 dB re 1 µPa and 145 dB re 1 µPa^{2}s SEL at 63 m, with all noise levels less than 180 dB re 1 µPa at all distances underwater. Neither Blackwell et al. (2004) nor Moulton et al. (2003) observed a negative behavioral response by ringed seals towards any construction noise, including pile driving (except helicopters passing overhead (Blackwell et al. 2004)), with the highest recorded densities of seals within 1 km of the development zone and seals approaching as close as 46 m to the pipe driving activity.

These studies (Table 27) report measured received levels and behavioral observations and could be included in the development of future behavioral risk functions when there are additional data.

Table 27. Summary of received levels and distances for behavioral responses to pile driving in both field and captive studies.

Species	RL range at response (SPL dB rms)	Distance range at Response (km)	Type of study
Harbor porpoise [1–9]	139 - 184	2.5 - 20	passive acoustic monitoring
Harbor porpoise [10–11]	136 - 168	NA	captive study
Bottlenose dolphin [12]	133.4 (SEL)	0.8	passive acoustic monitoring
California sea lion [13]	165 - 169	NA	captive study
Ringed seal [14–15]	NA (108 - 145)	NA (0.5 – 1)	monitoring
Harbor seal [16–19]	163 - 166	4 - 25	monitoring
Gray seal [16–18]	163	4	monitoring

[1] Benhemma-Le Gall et al. (2021); [2–4] Tougaard et al. (2003, 2005, 2009); [5–6] Brandt et al. (2011; 2016); [7] Dähne et al. (2013); [8] Scheidat et al. (2011); [9] Thompson et al. (2010); [10] Lucke et al. (2011); [11] Kastelein et al. (2013c); [12] Graham et al. (2017); [13] Finneran et al. (2003); [14] Moulton et al. (2003); [15] Blackwell et al. (2004); [16] Edrén et al. (2010); [17] Teilmann et al. (2004); [18] Skeate et al. (2012); [19] Russell et al. (2016).

3.2.4 Behavioral Response Thresholds of Explosives

If more than one explosive event occurs within any given 24-hour period within a Navy training or testing activity, criteria are applied to predict the number of animals that may have a significant behavioral reaction. For events with multiple explosions, the behavioral threshold used in this analysis is 5 dB less than the TTS onset threshold. This value is derived from observed onsets of behavioral response by test subjects (bottlenose dolphins) during non-impulse TTS testing (Schlundt et al. 2000).

For single explosions at received sound levels below hearing loss thresholds, the most likely behavioral response is a brief alerting or orienting response. Since no further sounds follow the initial brief impulses, significant behavioral reactions would not be expected to occur. If a significant response were to occur, the Navy assumes it would occur within the range to auditory effects (AINJ and TTS). Some multiple explosive events, such as certain naval gunnery exercises, may be treated as a single event because a few explosions occur closely spaced within a very short time (a few seconds).

There are very little experimental or observational data on behavioral responses by marine mammals to explosives. One passive acoustic study recorded the use of seal bombs (deterrent devices) in Monterey Bay by fishermen (Simonis et al. 2020) and estimated potential distances to impacts for harbor porpoises. The authors estimated that SELs of 130-151 dB re 1 μPa^2s could extend as far out as 65 – 118 km and could lead to behavioral responses. However, most of the energy in these sounds is below 250 Hz, and the energy above 1 kHz attenuates by 25 km, so it is very unlikely that harbor porpoises would detect the sounds at great distances, much less respond to them.

4 SEA TURTLE AUDITORY AND BEHAVIORAL CRITERIA AND THRESHOLDS

4.1 AUDITORY WEIGHTING FUNCTIONS AND EXPOSURE FUNCTIONS

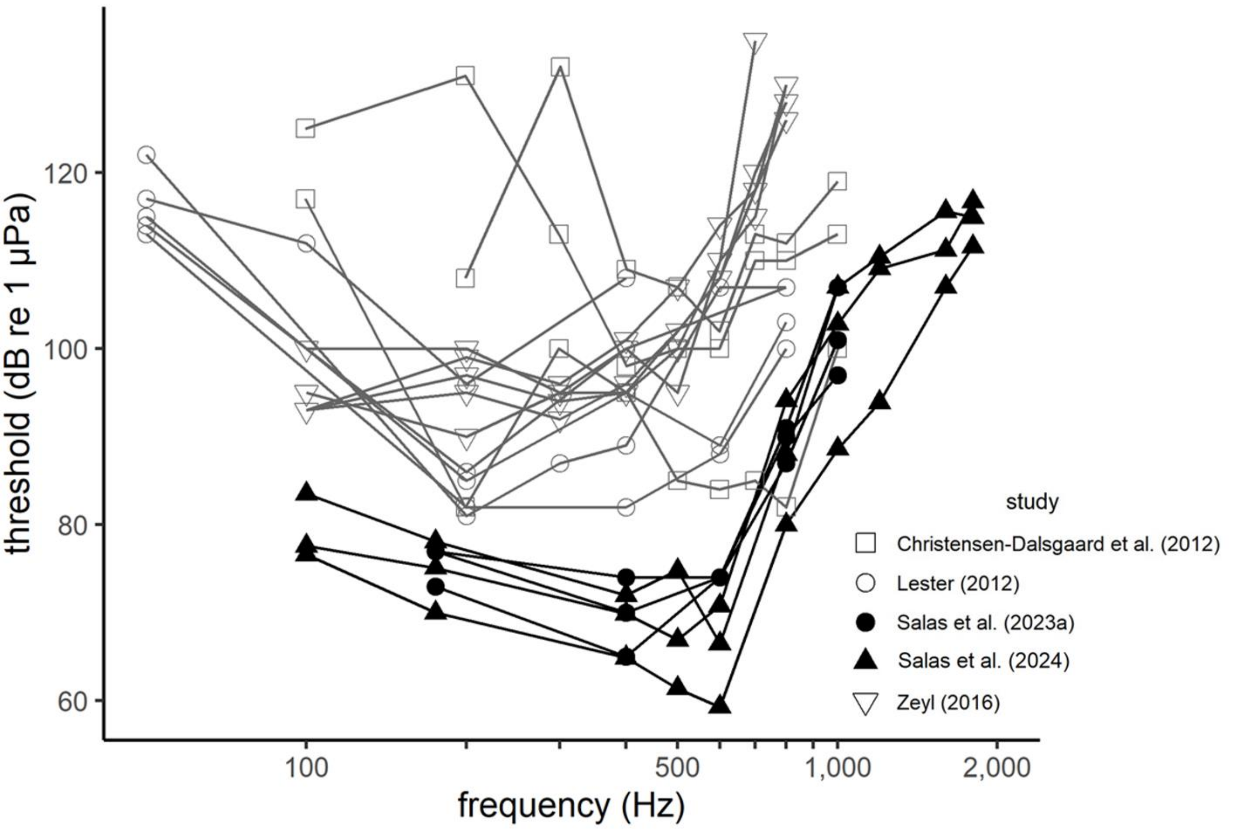
Navy thresholds for predicting auditory effects of non-impulsive and impulsive sounds on marine animals focus on defining the onset of temporary threshold shift (TTS) and the onset of auditory injury (AINJ) which includes, but is not limited to, permanent threshold shift (PTS). No studies have measured TTS in sea turtles, but two studies have examined underwater TTS in freshwater turtles (Salas et al., 2023a, 2024). The onset of TTS was defined as the SEL at which post-exposure hearing thresholds were 6 dB above the mean of measured typical (control) thresholds for each individual turtle. These onset values for freshwater turtles were extrapolated to determine a TTS onset level for non-impulsive sounds in sea turtles. The onset of AINJ for non-impulsive sources was 20 dB above the TTS onset level (unchanged from Phase 3). The details, rationale and steps of this process and the method for determining impulsive noise TTS and AINJ onset levels are described in the sections below.

4.1.1 Composite Audiograms

A comparison between composite audiograms for freshwater turtles (FW) and sea turtles (ST) allowed for FW TTS data to be applied to ST. Specifically, the lowest thresholds of hearing for FW and ST were compared. Most turtle audiogram data have been obtained by auditory-evoked potential (AEP) measurements, though some behavioral hearing data exist. Turtle hearing is restricted to below approximately 2 kHz, and sea turtles have a relatively narrower frequency range of best hearing and higher thresholds at the best frequency compared to marine mammals. However, sea turtles are often more sensitive to lower frequencies than many marine mammals. Freshwater turtles are generally more sensitive to sound than sea turtles. In this analysis, all freshwater and sea turtle audiogram data were considered.

4.1.1.1 Freshwater Turtle (FW)

All best-available freshwater turtle underwater audiogram data from the scientific literature were evaluated. Data were available from seven species across five studies (Figure 46). The six individuals from two studies [Red-eared sliders, *Trachemys scripta elegans*, n = 3 (Salas et al., 2023a); Eastern painted turtles, *Chrysemys picta picta*, n = 3 (Salas et al., 2024)] for which TTS data exist exhibited lower hearing thresholds when compared with other FW hearing data (Figure 46). Because of the approximately 20 dB difference between the lowest thresholds for the subjects with TTS data (black data points in Figure 46) and the lowest thresholds measured in other studies (gray data points in Figure 46.), only data from subjects in the TTS studies were used in the FW composite audiogram. A composite audiogram using all available freshwater turtle audiogram data would not have accurately represented the relationship between the FW hearing thresholds and onset TTS data. There are multiple possible reasons for the lower thresholds observed by Salas et al. (2023a, 2024); including but not limited to the methods used both to collect and to analyze hearing data. See Salas et al. (2023b) for a detailed description of how different methods affect resulting threshold values, and Salas et al. (2023a) for a discussion of how the audiograms from red-eared sliders in that study compare to other studies.



- Each line shows an individual turtle subject or average audiogram from multiple subjects, and each symbol denotes the study. Only data in black were used to generate the FW composite audiogram.
- Open square = Christensen-Dalsgaard et al. (2012), *Trachemys scripta* $\mathrm{n} = 3$
- Open circle = Lester (2012) *Malaclemys terrapin* $\mathrm{n} = 5$
- Open triangle = Zeyl (2016) *Trachemys scripta* $\mathrm{n} = 7$ averaged; *Terrapene carolina* $\mathrm{n} = 11$ averaged, *Kinosternon subrubrum* $n = 1$; *Apalone spinifera* $\mathrm{n} = 1$; *Sternotherus minor* and *S. odoratus* $\mathrm{n} = 9$ averaged
- Closed circle = Salas et al. (2023a); *Trachemys scripta elegans* $\mathrm{n} = 3$
- Closed triangle = Salas et al. (2024), *Crysemys picta picta* n = 3

Figure 46. Freshwater turtle underwater audiogram data.

The audiograms of the six individual freshwater turtles with TTS data were described by the function:

$$s_t = m_i \log_{10}\left(\frac{f}{f_0}\right) + y_0 \tag{9}$$

where S_t is the signal level (in dB) at threshold for the frequency f (in kHz), and m, f_0, and y_0 are fitting parameters. The FW composite audiogram was fit using segmental linear regression (i.e., piecewise linear regression).

The function is comprised of two line segments each fit by this equation, where the slope of the line segment m is negative if $f < f_0$ and positive if $f \geq f_0$. This allowed for the best fit of the FW audiogram data and the most accurate determination of the lowest hearing threshold, which was imperative for determining sea turtle TTS onset (see Section 4.1.2.1 Extrapolation of ST onset levels from FW data, below).

Figure 47 shows the median included FW audiogram data (Salas et al., 2023a, 2024) and the fitted composite audiogram function from Eq. (9). The median was chosen to reduce the influence of outliers and for consistency with how composite audiograms were generated for marine mammals. Table 28 lists the best fit parameter values from Eq. (9) for the FW composite audiogram.

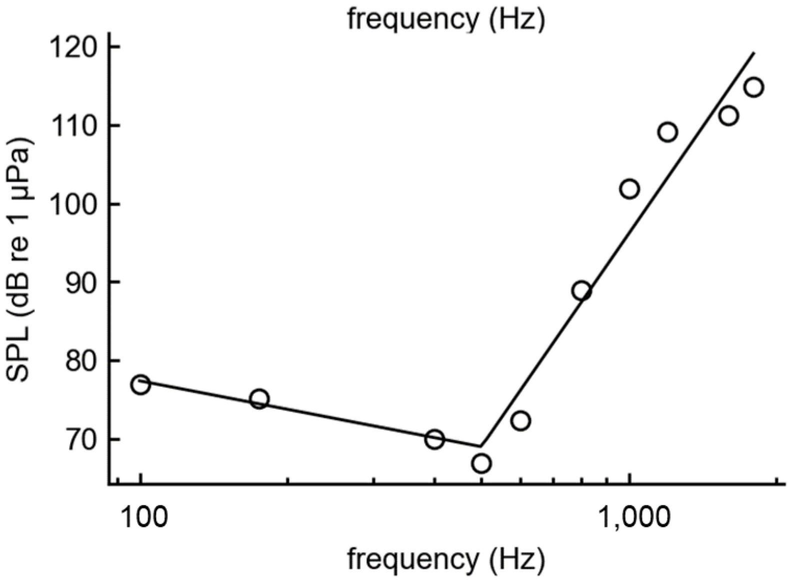


Figure 47. Freshwater turtle (FW) median audiogram data fit with (Eq. 9).

Table 28. FW composite audiogram best fit parameters.

Eq. (9) parameters	Best fit value	Units
f_0	500	Hz
y_0	69	dB
m_1	-12	dB/decade
m_2	90	dB/decade

4.1.1.2 Sea Turtle (ST)

All best-available underwater sea turtle AEP and behavioral hearing threshold data from the scientific literature were considered. The Phase 3 composite audiogram for sea turtles was comprised of the median threshold value at each frequency for individuals from 5 species (U.S. Department of the Navy, 2017). No new sea turtle audiogram data have been published since Phase 3, but the methodology for deriving the ST composite audiogram was updated for Phase 4, and data from all individual turtles was re-examined.

Data from six individuals that had been included in Phase 3 were excluded in the Phase 4 analysis. Data from *Chelonia mydas* C (Bartol & Ketten, 2006) were excluded for exhibiting an abnormal audiogram shape for the species, and data from five individuals were excluded for lacking a minimum of three frequencies at which auditory sensitivity was measured (see Table 29). This minimum number of data points for each individual allowed a subjective determination as to whether the individual exhibited a normal audiogram shape and indications of masked or elevated thresholds. This is consistent with the methods used for the inclusion of individual audiograms in marine mammals. Underwater audiogram data from loggerhead sea turtles (Lavender et al., 2014) was considered but excluded in both Phase 3 and Phase 4 for exhibiting elevated thresholds and abnormal audiogram shapes. The resulting Phase 3 and Phase 4 ST composite audiograms are shown in Figure 50(a).

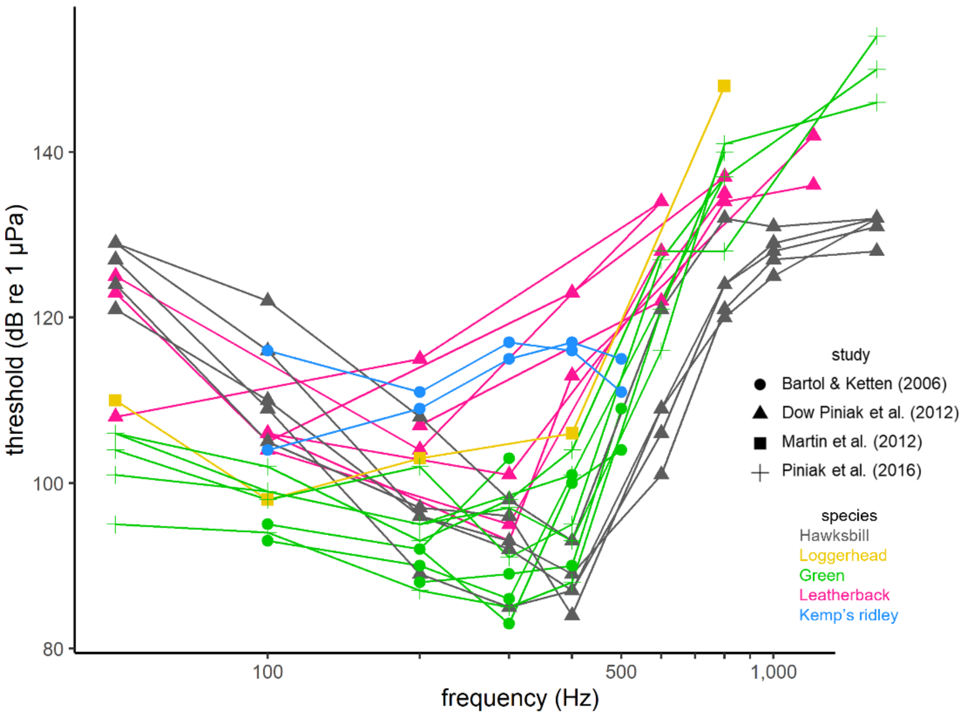
Table 29. Included individual sea turtle audiogram data.

Study	Species	Individual Subjects	
		Phase 3	Phase 4
Bartol and Ketten (2006)	*Chelonia mydas*	1, 2, D, C, X, 6	1, 2, D, 6
	Lepidochelys kempii	1E, 1N	1E, 1N
Martin et al. (2012)	*Caretta caretta*	female 31[1]	female 31
Piniak et al. (2016)[2]	*Chelonia mydas*	R1, L2, R3, L3A, L4[3]	R1, L2, R3, L3A, L4
Piniak et al. (2012)	*Dermochelys coriacea*	11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21	15, 16, 17, 18, 19, 20, 21
	Eretmochelys imbricata	3, 4, 6, 7, 10	3, 4, 6, 7, 10

[1] Both AEP and behavioral audiogram data was available for this subject, but only the behavioral data was used in both Phase 3 and Phase 4.

[2] In Phase 3, Dow Piniak et al., (2012) was cited for the same *Chelonia mydas* subjects that were later published in a peer-reviewed scientific journal and are now cited as Piniak et al., (2016).

[3] Subject L4 was listed twice (L4 and L4A) in Phase 3, but L4 was a single subject for which two audiograms were measured, and the average of the two audiograms was used in both Phase 3 and Phase 4.



- Each line shows an individual turtle subject, and each symbol denotes the study.
- Each species is represented using a different color:
- *Eretmochelys imbricata* in gray (n=5)
- *Caretta caretta* in yellow (n=1)
- *Chelonia mydas* in green (n=9)
- *Dermochelys coriacea* in pink (n=7)
- *Lepidochelys kempi* in blue (n=2)
- All audiograms plotted here were included in the Phase 4 ST composite audiogram. See Table 29 for additional information.

Figure 48. Sea turtle (ST) underwater audiogram data.

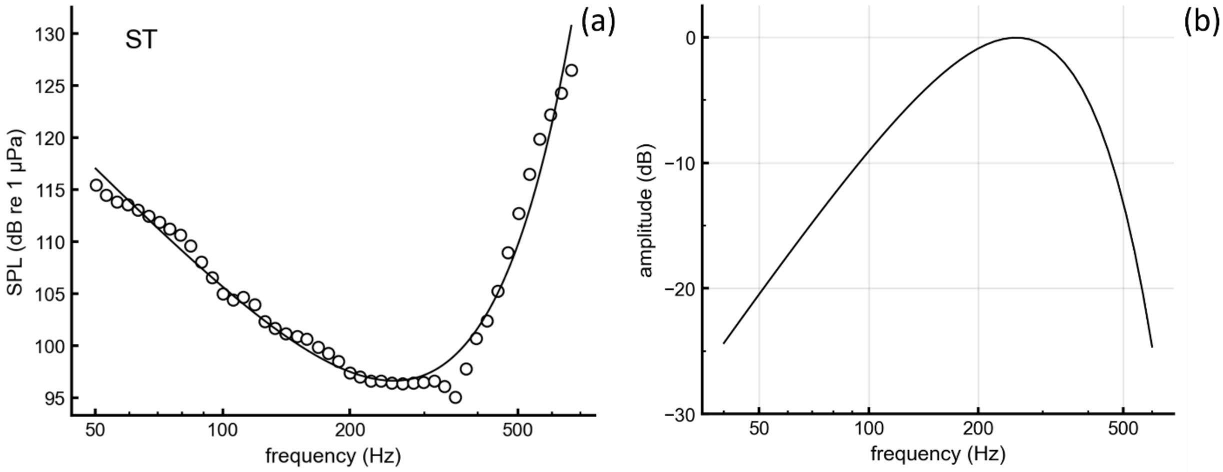
Since the sea turtle audiogram data was sourced from multiple studies (Figure 48), a common set of frequency values was necessary. Therefore, frequency values for each individual turtle were interpolated with frequencies spaced at 1/12-octave intervals, encompassing frequencies up to 700 Hz (inclusion of audiogram data above 700 Hz disrupted the composite audiogram curve fit). Threshold values between sequential data points in each dataset were obtained at the 1/12 octave frequencies by linear-log interpolation (linear thresholds, logarithmic frequencies, see Figure 3 in U.S. Department of the Navy, 2024). Then the median threshold value was calculated at each frequency and fit by the function:

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

where $T(f)$ is the threshold at frequency f (in kHz), and T_0, F_1, F_2, A, and B are fitting parameters. Median threshold values were used to reduce the influence of outliers. In Phase 3, the ST median threshold values were used to create a composite audiogram in place of a fitted curve; but here Eq. (10) was fit to the median interpolated threshold data (see Figure 49a). The resulting best fit parameters are provided in Table 30. This function was used instead of Eq. (9) because it provided a more realistic Ushaped composite audiogram shape, which was necessary for the derivation of the ST TTS exposure function. The weighting function (see Figure 49b) is based on the composite audiogram and is defined as:

$$T(f) = W_0 - A\log_{10}\left(1 + \frac{F_1}{f}\right) - \left(\frac{f}{F_2}\right)^B \tag{11}$$

where $T(f)$ is the threshold at frequency f (in kHz), and W_0, F_1, F_2, A, and B are fitting parameters. All fitting parameters are the same as in Table 30, except that W_0 = 225.1 dB.



- (a) Composite audiogram. Data points representing the median of interpolated thresholds from Figure 48 were fit with Eq. (10).
- (b) Weighting function [Eq. (11)]

Figure 49. Sea turtle (ST) composite audiogram and weighting function.

Table 30. ST composite audiogram best fit parameters.

Eq. (10) parameters	Best fit value [1]	Units
T_0	-128.5	dB
A	41.56	-
F_1	39,640	kHz
F_2	0.08069	kHz
B	1.944	-

[1] Minimum threshold was 96.6 dB at 255 Hz

4.1.2 Non-impulsive TTS data and TTS and AINJ Onset Levels

No TTS data exist for sea turtles (ST). In Phase 3, ST TTS onset for non-impulsive sound sources was set to 200 dB SEL (weighted) based on data from fish (Halvorsen et al., 2013; Halvorsen et al., 2012), but in Phase 4, this onset was determined by extrapolating from TTS data in freshwater (FW) turtles. In both Phase 3 and Phase 4, a 20 dB difference between TTS and AINJ onset was applied for non-impulsive sounds. This section describes these steps in detail.

4.1.2.1 Extrapolation of ST Onset Levels from FW Data

Two studies measured TTS in freshwater turtles due to continuous (non-impulsive) broadband (50 – 1,000 Hz) noise exposure (Salas et al., 2023a, 2024). Hearing thresholds (AEPs) were measured after noise exposure or after no noise (control). Thresholds were measured at five different time points after the sound exposure, and the magnitude of TTS for an individual sound exposure was calculated as the difference between the mean of a subset of control thresholds for that individual turtle and the highest of the five post-exposure measurements.

TTS onset was determined by a linear interpolation of the data for each individual turtle to find the SEL at which 6 dB of TTS occurred (Salas et al., 2023a, 2024). Red-eared sliders were tested at 400 Hz, but eastern-painted turtles were tested at both 400 Hz and 600 Hz. To avoid overrepresentation of the eastern-painted turtle species, and because all individual turtles exhibited lower onsets at the 600 Hz hearing test frequency, only the TTS onset data for the 600 Hz test frequency were used. For three red-eared sliders with individual onset TTS of 166, 146, and 164 dB re 1 µPa^{2}s SEL, and three eastern painted turtles with individual onset TTS of 154, 151, and 156 dB re 1 µPa^{2}s SEL, the mean unweighted TTS onset level was 156 dB re 1 µPa^{2}s.

To convert this unweighted TTS onset value to a weighted SEL, sound spectra of the exposures provided by Salas et al. (2023a) and the best fit parameters from the FW composite audiogram function were used (see Table 30). The average difference between weighted (based on the composite audiogram) and unweighted SELs from the sound spectra was determined and then added to the 156 dB re 1 µPa^{2}s average unweighted TTS onset SEL, which yielded a weighted non-impulsive FW TTS onset of 150 dB re 1 µPa^{2}s SEL. Since the minimum threshold of the ST composite audiogram function was 28 dB higher than the FW minimum threshold value, this numeric difference was added to the weighted FW TTS onset level (150 dB re 1 µPa^{2}s SEL) to yield a weighted ST TTS onset level of 178 dB re 1 µPa^{2}s SEL (see Table 31). This method is consistent with how TTS onset was estimated for the marine mammal groups that lack TTS data (U.S. Department of the Navy, 2024).

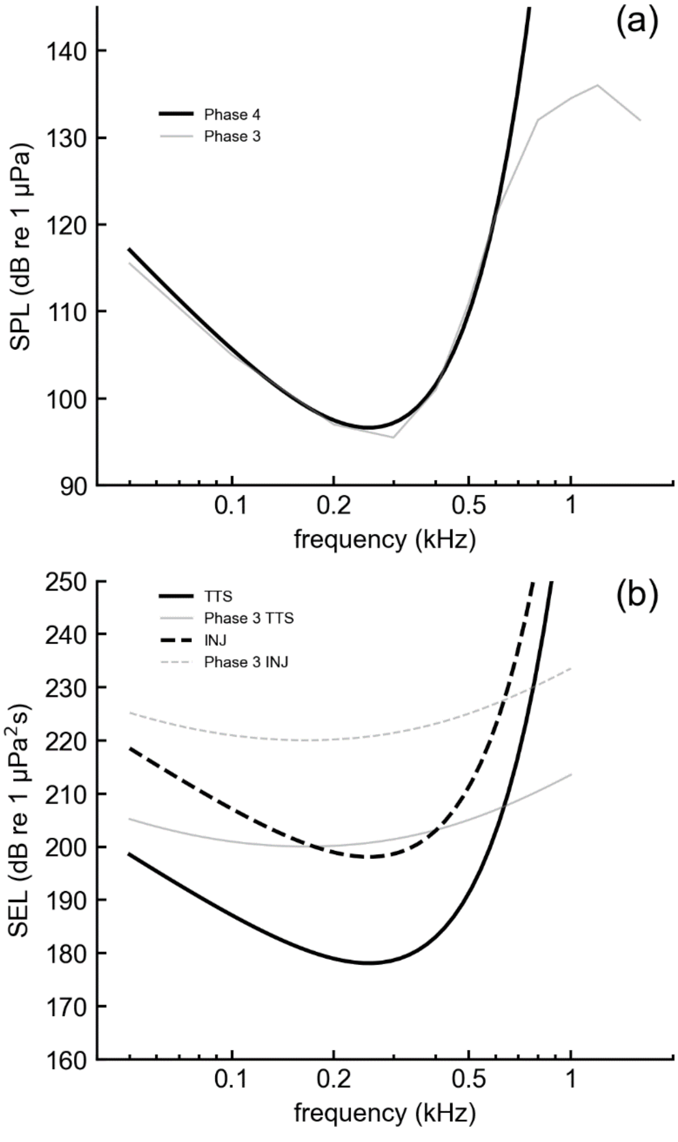
Table 31. Parameters used to estimate weighted non-impulsive TTS onset level for ST.

Parameter	Value
Unweighted average FW TTS onset level	156.3 dB SEL [1]
Average difference between unweighted and weighted FW sound exposures	-5.8 dB SEL
Weighted FW TTS onset level	150.5 dB SEL
Minimum FW composite audiogram threshold	69.0 dB SPL
Minimum ST composite audiogram threshold	96.6 dB SPL
ST – FW minimum threshold difference	27.6 dB SPL
Weighted ST TTS onset level	178.1 dB SEL

[1] 1Onset TTS values for individual turtles were: RES01 = 165.8, RES04 = 146.3, RES05 = 164.2, EPT02 = 154.4, EPT03 = 151.4, EPT04 = 155.7.

Like other taxa, TTS susceptibility and recovery rates in freshwater turtles depended on the individual subject, and recovery rate depended on the magnitude of the initial shift (Salas et al., 2023a, 2024). Generally, red-eared sliders recovered from TTS of greater than 20 dB after 81 minutes and took 41 minutes to recover from TTS less than 20 dB. Most TTS recovered within approximately 1 hour, but some of the larger shifts (approximately 20–40 dB) took longer than 1 hour to recover. The longest observed recovery time was between 2 and 5 days post-exposure for a 40 dB TTS (Salas et al., 2023a). Considering the lack of PTS or other auditory injury data in turtles, the onset of auditory injury (AINJ) was set 20 dB above the TTS onset level, which equaled a weighted level of 198 dB re 1 µPa^{2}s SEL. This is the same relationship between onset TTS and onset AINJ (PTS) that was used in Phase 3 and is supported by the difference in recovery time observed for shifts > 20 dB in freshwater turtles described above.

The ST exposure functions shown in Figure 50b were generated by anchoring Eq. 10, (the composite audiogram function) to the TTS and AINJ onset levels (178 dB re 1 µPa^{2}s SEL and 198 dB re 1 µPa^{2}s SEL respectively) at the best frequency of hearing (255 Hz, see Figure 49 and Table 30). The exposure function is identical to Eq. 10, except that the parameter T_0 is replaced by E_0, which is equal to -47.14 dB for the TTS exposure function, and -27.14 dB for the AINJ exposure function.



(a) Composite audiogram.

(b) Exposure functions for non-impulsive TTS (solid lines) and AINJ (dashed lines).

Phase 3 functions are shown in thin gray lines and Phase 4 functions are shown in thicker black lines.

Figure 50. Phase 4 comparison to Phase 3 for sea turtles (ST).

4.1.3 Impulsive TTS and AINJ Onset Levels

For impulsive sound sources, a dual metric (both SEL and peak SPL) was used. The TTS onset levels for non-impulsive sources were used to derive impulsive noise onset levels for ST (Table 32). The methods were consistent with the Phase 3 approach, but values were updated to reflect Phase 4 analyses.

The Phase 3 analysis applied the average difference between SEL-based non-impulsive TTS onset and SEL-based impulsive TTS onset that was found for marine mammals. In Phase 4, this difference was -9.2 dB and yielded a threshold of 169 dB re 1 μPa^{2}s for ST SEL-based TTS onset. This results in a substantially lower threshold than the > 186 dB re 1 μPa^{2}s recommended for sea turtles by Popper et al. (2014). Popper et al. (2014) made no recommendations for peak SPL-based TTS thresholds for sea turtles.

In Phase 3 it was assumed that, given the high hearing thresholds of sea turtles relative to marine mammals, the turtle peak SPL-based threshold would likely be higher than marine mammals. Applying the same assumption in Phase 4, the ST peak SPL TTS onset for impulsive sounds was set to match the highest marine mammal value, which is 224 dB re 1 μPa for Phase 4.

Since data do not exist for AINJ due to impulsive sounds in turtles, the Phase 3 methods were retained for Phase 4. The AINJ thresholds were 15 dB higher than the SEL-based TTS threshold, and 6 dB higher than the peak SPL based TTS threshold (Southall et al., 2007a; Southall et al., 2019a; U.S. Department of the Navy, 2017). Impulse TTS and AINJ onset levels for Phase 4 are shown in Table 32.

Table 32. Phase 3 and Phase 4 TTS and AINJ onset levels for sonar (non-impulsive) and explosive (impulsive) sound sources in sea turtles.

	Phase 3		Phase 4	
	TTS	AINJ (PTS[2])	TTS	AINJ
Non-impulsive onset SEL (weighted) [1]	200	220	178	198
Impulsive onset SEL (weighted)	189	204	169	184
Impulsive onset Peak SPL	226	232	224	230

For weighted SEL onsets, units are dB re 1 μPa^2 s.

For impulsive peak SPL onsets units are dB re 1 μPa.

[1] The weighted non-impulsive thresholds by themselves only indicate the TTS/AINJ threshold at the most susceptible frequency (the exposure function shape is shown in Figure 50 part b).

[2] Auditory injury (AINJ) was previously referred to as permanent threshold shift (PTS). The new terminology acknowledges that auditory injury may occur without PTS.

4.2 BEHAVIORAL RESPONSE THRESHOLDS

Sea turtle behavioral responses to Navy relevant sound sources are poorly understood and limited data exist. Coupled with limited hearing capabilities and an understanding of how sea turtles use sound, it is challenging to derive acoustic and explosive behavioral response thresholds for sea turtles. Although the results of one study have become available since Phase 3 (Kastelein et al., 2023b), existing Phase 3 behavioral response thresholds were retained for Phase 4, and a threshold for exposure to multiple explosions consistent with existing methods (U.S. Department of the Navy, 2024) was applied. Values are summarized in Table 33 and the derivation of thresholds is described below.

Table 33. Phase 4 Behavioral response thresholds for sea turtles.

Source	dB SPL rms (unweighted)	dB SEL (cumulative; weighted)
Air guns	175	-
Pile driving	175	-
Sonar ≤ 2 kHz	175	-
Explosives	-	164

Weighted cumulative SEL thresholds in dB re $1\mu\text{Pa}^2\ \text{s}$ and unweighted SPL rms thresholds in dB re $1\mu\text{Pa}$.

The root mean square and sound exposure level calculations are based on the duration defined by the 5% and 95% points along the cumulative energy curve and captures 90% of the cumulative energy in the impulse.

4.2.1 Air Guns

During two air gun exposure studies (McCauley et al., 2000b; O'Hara & Wilcox, 1990), sea turtles were exposed to air gun shots over long durations (approximately 1-2 hours total of a traveling air gun and 20-36 hours total of a stationary air gun, respectively). McCauley et al. (2000b) observed erratic swimming with caged sea turtles, possibly indicative of an agitated state, at received levels above 175 dB re 1μPa SPL rms. O'Hara & Wilcox (1990) did not measure levels at which sea turtles confined in a large canal exhibited active avoidance, however, McCauley et al. (2000b) estimated this occurred at received levels of 175-176 dB re 1μPa SPL rms. McCauley et al. (2000b) also found that air gun signals were better characterized using SEL and determined that the SPLs at which behavioral responses occurred would have an SEL 11.4-14.6 dB lower than the SPL. For an SPL of 175 dB re 1 μPa, the comparable SEL for a single air gun shot would be 163.6 – 160.4 dB re 1 $\mu\text{Pa}^2\text{s}$. DeRuiter and Doukara (2012) observed diving behavior as an air gun array (source level = 252 dB re 1 μPa peak, duty cycle = 19.4 s) passed an aggregation of sea turtles resting at the water surface at a distance of approximately 130 m. However, it was not possible to distinguish whether turtles dove in response to the air gun sounds or the proximity of the vessel and towed array. A summary of sea turtle behavioral responses to seismic surveying or air gun noise is available in Table 1 of Nelms et al. (2016).

The existing Phase 3 sea turtle behavioral response criteria for air guns, developed with NMFS and based on the findings from McCauley et al. (2000b), was retained for Phase 4. A threshold of 175 dB re 1 μPa SPL rms is used to estimate sea turtle behavioral reactions to repeated air gun firing during Navy testing activities. The root mean square and sound exposure level calculations for air guns are based on the duration defined by the 5 and 95 percent points along the cumulative energy curve and captures 90 percent of the cumulative energy in the impulse.

4.2.2 Pile Driving

Impact pile driving produces repetitive, impulsive sounds potentially over multiple minutes, similar to repeated air gun shots. In the absence of observed sea turtle behavioral responses to pile driving collected in situ with measured or modeled received levels, the existing Phase 3 sea turtle behavioral response criteria for pile driving, developed with NMFS and based on exposure to air guns (McCauley et al., 2000b), was retained for Phase 4. The received sound level at which sea turtles are expected to actively avoid air gun exposures, 175 dB re 1 μPa SPL rms (McCauley et al., 2000b) is expected to be the received sound level at which sea turtles would actively avoid exposure to impact and vibratory pile driving noise. The root mean square and sound exposure level calculations for pile driving is based on the duration defined by the 5 and 95 percent points along the cumulative energy curve and captures 90 percent of the cumulative energy in the impulse.

4.2.3 Sonar

The sea turtle composite audiogram and studies of in-water hearing abilities indicate hearing detection generally lies between 50 and 1600 Hz, with maximum sensitivity between 100 and 400 Hz. In addition, the qualitative sound exposure guidelines developed by Popper et al. (2014) estimated the risk to sea turtles from low-frequency sonar to be low, and mid-frequency sonar to be non-existent. Therefore, sea turtles are only analyzed to behaviorally respond to low frequency sonar and other active acoustic sources up to 2 kHz.

Studies of reptile responses to underwater non-impulsive sounds are limited. Lenhardt (1994) used very low frequency vibrations (<100 Hz) coupled to a shallow tank to elicit swimming behavior responses by two loggerhead sea turtles. Watwood et al. (2016) tagged green sea turtles with acoustic transponders and monitored them using acoustic telemetry arrays in Port Canaveral, Florida. Sea turtle residency was monitored before, during, and after exposure to mid-frequency active sonar during a routine pier-side submarine sonar test. No significant long-term displacement was demonstrated by the sea turtles in this study.

Given less sensitive hearing thresholds and anatomical differences between sea turtle and marine mammal hearing mechanisms, marine mammals are not a suitable surrogate for estimating sea turtle behavioral response to sonar. Popper et al. (2014) proposed that fish without specialized auditory adaptations for higher frequency hearing may provide a better approximation for estimating sea turtle behavioral responses to sonar due to similar hearing sensitivity and frequency ranges. However, given the current limited understanding of how sea turtles use sound, it is unclear if they would behaviorally respond to sound in a similar way as fish.

Kastelein et al. (2023b) exposed two green and two hawksbill sea turtles to a wide variety of potential acoustic deterrent signals (> 200 Hz) including Helicopter Long-Range Active Sonar (HELRAS) down sweeps (1.3 – 1.44 kHz). No behavioral responses were observed to the HELRAS, pure tones, impulsive sounds, or killer whale vocalizations, at levels of approximately 173 dB re 1 µPa SPL. Behavioral responses were observed to eighteen different sounds with various spectro-temporal characteristics, duty cycles and received levels. Of those, four sound types with Navy-relevant signal characteristics (frequency modulated and upsweep), had an approximated received level below the 175 dB re 1 µPa SPL threshold. However, no consistent relationship between signal level and behavioral response was observed, and contextual factors appeared to explain some of these responses. The baseline behavioral state of the turtle appeared to influence the likelihood of a response, with bottom-resting turtles exhibiting little to no responses. The reverberant, shallow environment of the testing pool, minimal controls in the experimental design, and absence of behavioral responses to impulsive sounds suggests that the results of this study should be interpreted with caution, and do not necessitate any changes to the criterion for sonar. However Kastelein et al. (2023b) support that sea turtles are most likely to respond to sounds in the 0.2 – 1 kHz frequency range, and that responses are context dependent.

In Phase 3 NMFS requested that the Navy apply the 175 dB re 1 µPa Pa SPL rms level used for nonexplosive impulsive sources (McCauley et al., 2000b) to estimate sea turtle behavioral response to sonar and other active acoustic sources (up to 2 kHz). This threshold value is consistent with the observation by Kastelein et al. (2023b) that sea turtles did not respond to sonar at levels of approximately 173 dB re 1 µPa SPL. In the absence of observed sea turtle behavioral responses to sonar collected in situ with measured or modeled received levels, the Navy will retain the Phase 3 threshold for Phase 4.

4.2.4 Explosives

No currently known studies have examined received levels at which sea turtles behaviorally respond to explosions. Based on sea turtle hearing abilities, they are likely able to detect the low frequency components of broadband impulsive noise from explosions. The qualitative sound exposure guidelines developed by Popper et al. (2014) estimated the risk to sea turtles from explosions to be high at near and intermediate ranges (tens to hundreds of meters respectively), and low at far ranges (thousands of meters).

In the absence of observed sea turtle behavioral responses to explosions collected in situ with measured or modeled received levels, the threshold for behavioral disturbance to multiple explosions is set 5 dB below the impulsive SEL-based TTS threshold. This approach is consistent with the derivation of the marine mammal behavioral response threshold to multiple explosions (U.S. Department of the Navy, 2024). For Phase 4, the behavioral response threshold for sea turtles exposed to multiple explosions is 164 dB re 1 $\mu Pa^2 s$ SEL. For a single explosion the behavioral response threshold is set to the impulsive TTS onset threshold of 169 dB re 1 $\mu Pa^2 s$ SEL. This approach is consistent with the derivation of the marine mammal behavioral response threshold to a single explosion (U.S. Department of the Navy, 2024). The root mean square and sound exposure level calculations for explosives are based on the duration defined by the 5 and 95 percent points along the cumulative energy curve and captures 90 percent of the cumulative energy in the impulse.

5 EXPLOSIVE NON-AUDITORY INJURY CRITERIA

5.1 INTRODUCTION

This section describes the criteria for estimating non-auditory physiological impacts on marine mammals and sea turtles due to underwater explosions. These criteria follow a similar methodology as past Navy explosive impact analyses (Finneran & Jenkins, 2012; U.S. Department of the Navy, 2001, 2008, 2017).

The effects of underwater explosions on marine mammals and sea turtles depend on a variety of factors including animal size and depth; charge size and depth; depth of the water column; and distance between the animal and the charge. The gas-containing organs (lungs and gastrointestinal tract) are most vulnerable to primary blast injury. Severe injuries to these organs are presumed to result in mortality (e.g., severe lung damage may introduce air into the cardiopulmonary vascular system, resulting in lethal air emboli).

Because gas-containing organs are more vulnerable to primary blast injury, adaptations for diving that allow for collapse of lung tissues with depth may make animals less vulnerable to lung injury with depth. Adaptations for diving include a flexible thoracic cavity, distensible veins that can fill space as air compresses, elastic lung tissue, and resilient tracheas with interlocking cartilaginous rings that provide strength and flexibility (Ridgway, 1972). Older literature suggested complete lung collapse depths at approximately 70 m for dolphins (Ridgway & Howard, 1979) and 20-50 m for phocid seals (Falke et al., 1985; Kooyman et al., 1972). Follow-on work by (Kooyman & Sinnett, 1982), in which pulmonary shunting was studied in harbor seals and sea lions, suggested that complete lung collapse for these species would be about 170 m and about 180 m, respectively. Evidence in sea lions suggests that complete collapse might not occur until depths as great as 225 m; although the depth of collapse and depth of the dive are related, sea lions can affect the depth of lung collapse by varying the amount of air inhaled on a dive (McDonald & Ponganis, 2012) This is an important consideration for all divers which can modulate lung volume and gas exchange prior to diving via the degree of inhalation and during diving via exhalation (Fahlman et al., 2009). Indeed, there are noted differences in pre-dive respiratory behavior with some marine mammals exhibiting pre-dive exhalation to reduce the lung volume (e.g., phocid seals [Kooyman et al., 1973]).

5.2 BACKGROUND

5.2.1 Available Data on Underwater Blast Injury to Marine Mammals and Sea Turtles

Data on blast injury to marine mammals and sea turtles is limited. Richardson et al. (1995) summarized past exposures and evidence of mortality or injury to wild marine mammals; animal proximity to explosions was generally not available, and the amount of data was overall insufficient to define injury criteria.

Since Richardson et al.'s (1995) summary, there has been one documented incident of mortalities to marine mammals after exposure to an explosion during Navy training. In 2011, three long-beaked common dolphins were immediately killed by exposure to a 3.97 kg net explosive weight charge placed on the seafloor in 48 feet (15 m) of water during an underwater detonation training activity at the Silver Strand Training Complex near San Diego, CA (for additional information, see Danil & St. Ledger [2011]). A fourth long-beaked common dolphin was found on-shore dead three days after the detonation with injuries consistent with blast exposure. The dolphins were in a pod of about 100-150 dolphins that swam into the mitigation zone preceding the detonation. The explosive device was set on a time-delay fuse.

Attempts to deter the animals' travel toward the detonation site were unsuccessful. Although the animals were seen approaching the blast area, the actual locations of the injured animals relative to the charge at the time of detonation are unknown. Upon necropsy, all four animals were found to have sustained typical mammalian primary blast injuries (Danil & St. Ledger, 2011).

Incidental impacts on sea turtles were documented for exposure to a single 1200-lb (540 kg) underwater charge off Panama City, Florida in 1981. The charge was detonated at mid-depth in water 120 feet (37 m) deep. Although details are limited, the following were recorded: at a distance of 500-700 ft. (150-200 m), a 400 lb. (180 kg) sea turtle was killed; at 1200 ft. (370 m), a 200-300 lb. (90-140 kg) sea turtle experienced “minor” injury; and at 2000 ft. (600 m) a 200-300 lb. (90-140 kg) sea turtle was not injured (O'Keeffe & Young, 1984).

5.2.2 Human Diver Exposure Data

Data from human divers are informative as they provide subjective descriptions of sensations experienced during blast exposures. Human divers were voluntarily exposed to underwater detonations to develop safety standards for human divers. Human diver exposures and impacts are described in Table 34 and Table 35.

Table 34. Human diver blast exposure for 1.25-lb charge at 15-ft. depth, diver on bottom in 20 ft. water depth Wright et al. 1950 (as cited in Cudahy & Parvin, 2001)

Range (ft. [m])	Described Sensation	Peak Pressure [1] (psi [dB re 1 µPa])	Impulse [1] (psi-ms [Pa-s])
120 (37)	Loud bang. Slight pressure on torso but no discomfort.	85 (235)	29 (200)
90-75 (27-23)	Bang on head but no discomfort to ears or torso.	120-150 (238-240)	35-45 (240–310)
50 (15)	Intense bang. Blow on head and chest.	240 (244)	65 (450)
40 (12)	Severe blow on head and torso. Body violently shaken but no sub-sternal pain.	300 (246)	76 (520)
35 (11)	Strong blow on head and torso. Brief paralysis of arms and legs. Dull ache in chest. Brief sub-sternal pain.	350 (248)	88 (610)
32 (10)	Violent blow on head. Brief paralysis of limbs. Sub-sternal pain lasting several hours. Shattering sensation but no permanent injury.	450 (250)	110 (760)

[1] Values were estimated by Wright et al.

Table 35. Human diver blast exposure for 5-lb charge at 15-ft. depth, diver on bottom in 20 ft. water depth (Wright et al. 1950 [as cited in Cudahy & Parvin, 2001])

Range (ft. [m])	Described Sensation	Peak Pressure [1] (psi)	Impulse [1] [psi-ms (Pa-s)]
110 (34)	Sound of intense bang.	16 (241)	75 (520)
100 (30)	Intense bang. Mild blow on chest.	175 (242)	85 (590)
90 (27)	Severe blow on chest.	195 (243)	95 (660)
80 (24)	Blow on head and torso. Body shaken. Brief paralysis of arms and legs.	220 (244)	105 (720)
75 (23)	Violent blow. Brief paralysis of limbs. Sub-sternal pain for 0.5-1 hour.	240 (244)	110 (760)
70	Violent blow. Temporary paralysis of limbs. Sub-sternal pain lasting several hours. Aural damage. Tongue lacerated. Mask blown off. Mild concussion.	260	115 (790)

[1] Values were estimated by Wright et al.

5.2.3 Available Data on Underwater Blast Injury to Terrestrial Mammals

Due to the scarcity of marine mammal data, development of explosive impact criteria relies on data from exposures of terrestrial animals to controlled underwater blasts. In the early 1970s, the Lovelace Foundation for Medical Education and Research conducted a series of tests in an artificial pond at Kirtland Air Force Base, New Mexico to determine the effects of underwater explosions on mammals, with the goal of determining safe ranges for human divers. During the tests, sheep, dogs, and monkeys were positioned at or near the water surface at 1, 2, and 10 ft. (0.3, 0.6, and 3 m) depths and at varying distance from charges in a large pool. Animals at 10 ft. depth were attached to a pressurized underwater breathing apparatus. Charges ranged from 0.5 to 8 lb. (0.23 to 6.3 kg) of pentolite and/or trinitrotoluene (TNT) placed at 10 ft. (3 m) depth. No deaths were observed from blast injuries. Mammals were sacrificed two hours after exposure, and damage to the lungs and gastrointestinal (GI) tract were examined. Specific physiological observations for each test animal are documented in Richmond et al. (1973).

Acoustic impulse was found to be the metric most related to degree of injury, and size of an animal's gas-containing cavities was thought to play a role in blast injury susceptibility (Richmond et al., 1973; Yelverton et al., 1973). The subject animals were exposed near the water surface; therefore, depth effects were not discernible in this data set. The resulting data were summarized in two reports (Richmond et al., 1973; Yelverton et al., 1973). For these shallow exposures of dogs, sheep, and monkeys (masses ranging from 3.4 to 50 kg) to underwater detonations, Richmond et al. (1973) reported that:

- An impulse of 34 psi-ms (230 Pa-s) resulted in about 50 percent incidence of slight lung hemorrhage. Below 20 psi-ms (140 Pa-s) there were no instances of slight lung hemorrhage.
- Some exposures at higher levels (up to 40 psi-ms [280 Pa-s]) resulted in no observable lung damage.
- About half of the animals had gastrointestinal tract contusions (with slight ulceration, i.e., some perforation of the mucosal layer) at exposures of 25-27 psi-ms (170-190 Pa-s).
- Lung injuries were found to be slightly more prevalent than GI tract injuries for the same exposure level.

Some limitations of this dataset are:

- Subjects were held at shallow depths or at the surface.
- Test animals were small compared to the range of marine mammal sizes.
- Only injuries evident at sacrifice/necropsy at two hours after exposure were considered (i.e., longer term survival rates were not considered).
- Lungs were expanded at depth because the animals were actively breathing air (unlike breath-hold divers).

Additionally, some control animals connected to the underwater breathing apparatus but not exposed to detonations exhibited lung damage or died. It is reasonable to assume that in some instances lung damage observed in animals exposed to detonations may have been caused or exacerbated by animal handling procedures or the underwater life support system.

While the above study was conducted to assess safe ranges for human swimmers, it is the best available data set for assessing non-auditory physiological impacts on marine mammals and sea turtles from explosives. The lungs of marine mammals are grossly similar in proportion to overall body size as those of terrestrial mammals, so the magnitude of lung damage in the tests may approximate the magnitude of injury to marine mammals when scaled for body size. However, within the marine mammals, (Piscitelli et al., 2010) observed that mysticetes and deeper divers (e.g., Kogiidae, Physeteridae, Ziphiidae) tend to have lung to body size ratios that are smaller and more similar to terrestrial animal ratios than shallow diving odontocetes (e.g., Phocoenidae, Delphinidae). Measurements of some shallower diving sea turtles (Hochscheid et al., 2007) and pinnipeds (Fahlman et al. 2014) show lung to body size ratios that are similar to shallow diving odontocetes, whereas the lung to body mass ratio of the deeper diving leatherback sea turtle is smaller (Lutcavage et al., 1992). The use of test data with smaller lung to body ratios results in a more conservative estimate of potential for damaging effects (i.e., lower thresholds).

Yelverton & Richmond (1981) conducted probit analyses of the Lovelace Foundation injury data and mortality data (i.e., defined as extensive lung injury discovered after animals were sacrificed and necropsied, as no mortalities were observed in two-hour observation period post exposure), relating likelihood of injury to impulse. The probit analyses were used to develop regression equations for 50 percent mortality and one percent mortality relating impulse to body mass for shallow water exposures.

$$\text{One percent mortality: } \ln(I) = 4.507 + 0.386 \ln(M) \tag{12}$$

where: *I* = impulse threshold for effect (Pa-s)
M = animal mass (kg)

5.2.4 Relating Injury to Partial Impulse and Depth: the Goertner Lung Injury Model

The regression equations developed by Yelverton & Richmond (1981) do not account for how an animal could be affected with increasing depth. Goertner (1982) examined how lung cavity size would affect susceptibility to blast injury by considering both animal size and animal depth. Animal depth relates to injury susceptibility in two ways: injury is related to the relative increase in explosive pressure over hydrostatic pressure, and lung collapse with depth reduces the potential for air cavity oscillatory damage. Goertner (1982) estimated the oscillation period of the lung air cavity based on animal size and depth (i.e., hydrostatic pressure).

5.2.4.1 Impulse Duration for Injury

Goertner (1982) assumed that the impulse necessary to cause lung damage is related to the amplitude of lung oscillations and must be delivered over a specified time period. To account for long duration positive pressures, such as could occur with broadening of the initial positive pressure pulse with shock wave decay, the concept of "partial impulse" is applied, described by (Bowen et al., 1968) as the impulse occurring over the time duration leading to maximum gas cavity compression. This duration is the lesser of the duration of the initial positive pressure or 20 percent of the estimated lung resonance period (T). To determine the lung resonance period, the lung is modeled as a spherical gas bubble. As such, the oscillation period of the lung shortens with increasing hydrostatic pressure as the bubble (lung) collapses. Ultimately, a depth is reached where sufficient impulse cannot be delivered during the shortened period to result in an injurious effect. Because this model does not account for damping of lung response by the surrounding tissues, it considers a maximum lung compressive response.

The derivation of the equation to estimate lung resonance period is described in Goertner (1982). When all substitutions are made, the reduced equation is:

$$T = 22.5\, M^{1/3}\, \frac{p_{atm}^{1/3}}{p_{hyd}^{5/6}} \tag{13}$$

where: M = animal mass (kg)
p_{hyd} = hydrostatic pressure (psi) = p_{atm} + ($\gamma_w D/144$)
p_{atm} = atmospheric pressure (psi)
γ_w = specific weight of water (lb/ft^3)
D = depth of animal (ft)

The steep-front, high-amplitude shock wave is the initial positive pressure amplitude used to calculate impulse exposure for damaging effect. The shock wave caused by an explosion in deeper water may be followed by several bubble pulses with lower peak pressures (about one-fifth the initial peak pressure for the first follow-on pulse) and lacking the steep pressure front of the initial explosive pulse (Urick, 1983). These bubble pulses are not considered when analyzing injury potential due to peak pressure or impulse, as these values are inherently lower for bubble pulse exposure than for initial exposure.

The impulse exposure would be affected by the depth of the charge and the depth of the receiving animal. If a charge is detonated closer to the surface or if an animal is closer to the surface, the time between the initial direct path arrival and the surface-reflected tension wave arrival is reduced, resulting in a steep negative pressure cut-off of the initial direct path impulse exposure. Two animals at similar distance from a charge, therefore, may experience the same peak pressure but different impulse at different depths.

5.2.4.2 Impulse Scaling for Animal Size and Depth

Goertner (1982) also developed a scaling parameter for impulse-based lung damage that relates impulse associated with an observed effect to animal size and ambient pressure (hydrostatic and atmospheric). Equation 2.9 in Goertner (1982) shows this relationship as follows (note that water density in the denominator is later dropped as a constant, so it is not shown here):

$$\frac{I}{A_D p_{hyd}^{1/2}} \tag{14}$$

where: I = impulse for onset of injury effect
A_D = lung (bubble) radius at depth, D

Air bubble size (as proxy for lung size) decreases with increasing hydrostatic pressure at depth per Boyle's Law:

$$A_D = A_{atm} \left(\frac{p_{atm}}{p_{hyd}} \right)^{1/3} \tag{15}$$

where: A_{atm} = lung radius at the surface

Substituting Equation 15 into Equation 14 and assuming that lung radius is proportional to the cube root of body mass, the complete impulse scaling parameter is obtained:

$$\frac{I}{M^{1/3}\left(p_{atm}^{1/3}\right)\left(p_{hyd}^{1/6}\right)} \tag{16}$$

This scaling parameter is used to develop impulse-based thresholds by substituting appropriate known values from test data (designated by subscript t) documented in Richmond et al. (1973), as follows:

$$\frac{I}{M^{1/3}\left(p_{atm}^{1/3}\right)\left(p_{hyd}^{1/6}\right)} = \frac{I_t}{M_t^{1/3}\left(p_{atm,t}^{1/3}\right)\left(p_{hyd,t}^{1/6}\right)} \tag{17}$$

Solving for impulse (I) and substituting $p_{\text{hyd}} = p_{\text{atm}} + \gamma_w D$ results in the generalized Goertner lung injury scaling equation:

$$I = CM^{1/3} \left(1 + \frac{\gamma_w D}{p_{atm}} \right)^{1/6} \tag{18}$$

$$\text{where: } C = I_t \left(\frac{p_{\text{atm}}^{1/2}}{M_t^{1/3} p_{atm,t}^{1/3} \left(p_{atm,t} + \gamma_{w,t} D_t\right)^{1/6}} \right) \tag{19}$$

5.3 CRITERIA AND THRESHOLDS FOR EXPLOSIVE INJURY AND MORTALITY

5.3.1 Impulse-based Threshold Equations

Injury data from the animal exposures to underwater detonations documented in Richmond et al. (1973) are substituted into Equations 18and 19 to develop specific threshold equations for onset of slight lung injury and onset of mortality. The reference test data sets are for the animals that exhibited an effect (i.e., slight lung injury and extensive lung injury) at the lowest received impulse in the Lovelace experiments (see Table 36). This lowest observed dose with an effect is used to develop the onset threshold equations due to the limitations of the Lovelace data set and lack of data specific to any marine mammals. There were numerous exposures in which animals received significantly higher impulses without either slight lung hemorrhage or extensive lung hemorrhage. In all cases, impulses at the test animals were received over a duration that was less than 20 percent of the lung resonance period.

Although no test animals died within two hours of blast exposure, longer-term survival rates were not studied. It is reasonable to assume for impact analysis that extensive lung hemorrhage is a level of injury that would result in wild animal mortality. Slight lung injuries, such as slight hemorrhage, are injuries from which an animal would be expected to recover and survive.

The values for other environmental constants for the test and analysis conditions are shown in Table 37.

Table 36. Lowest experimental impulse exposures with injurious effects (Richmond et al., 1973)

Observed Effect	extensive lung hemorrhage	slight lung hemorrhage
Impulse, I	44.4 psi-ms (306 Pa-s)	22.8 psi-ms (157 Pa-s)
Animal Depth, D	2 ft.	10 ft.
Animal Mass, M	34 kg	42 kg

Table 37. Environmental constants at the experiment site (Richmond et al., 1973)

Constant	Value
Atmospheric pressure at test site[1] $p_{atm,t}$	12 psi
Atmospheric pressure at sea level, p_{atm}	14.7 psi
Specific weight of fresh water[1] $\gamma_{w,t}$	62.4 lb./ft.^{3}
Specific weight of sea water, γ_w	64 lb./ft.^{3}

[1] Tests were conducted in a freshwater man-made pond. The reported atmospheric pressure at the test site was 12 psi.

Use of the above values results in threshold equations for onset mortality and onset slight lung injury (SLI) as follows:

$$I_{\text{onset}\,SLI} = 47.5M^{1/3}\left(1+\frac{D}{10.1}\right)^{1/6}\ \text{Pa-s} \tag{20}$$

$$I_{\text{onset mortality}} = 103M^{1/3}\left(1+\frac{D}{10.1}\right)^{1/6}\ \text{Pa-s} \tag{21}$$

where: I = Impulse threshold (Pa-s)
D= depth of animal (m)
M= animal mass (kg)

This duration is the lesser of the duration of the initial positive pressure or 20 percent of the estimated lung resonance period (T) as discussed in 5.2.4.1 (Impulse Duration for Injury).

A comparison between the test exposure with the lowest impulse associated with severe lung injury shown in Table 36 (M = 34 kg, I = 306 Pa-s) and the one percent mortality impulse threshold predicted by Equation 12 (the one percent mortality regression equation for the Lovelace shallow water explosive exposures) for a 34-kg animal (I = 354 Pa-s) shows that the experimental measured impulse is lower than the value predicted using the regression equation.

5.3.2 Peak Pressure Threshold

Peak pressure contributes to the “crack” or “stinging” sensation of a blast wave, compared to the “thump” associated with received impulse. High peak pressures can cause damaging instantaneous tissue distortion. Older military reports documenting exposure of human divers to blast exposure generally describe peak pressure exposures around 100 psi (237 dB re 1 µPa peak) to feel like slight pressure or stinging sensation on skin, with no enduring effects (Christian & Gaspin, 1974).

Goertner (1982) suggested a peak overpressure GI tract injury criterion because the size of gas bubbles in the GI tract are variable, and their oscillation period could be short relative to primary blast wave exposure. The potential for GI tract injury, therefore, may not be adequately modeled by the single oscillation bubble methodology used to estimate lung injury due to impulse. Like impulse, however, high instantaneous pressures may damage many parts of the body, but damage to the GI tract is used as an indicator of any peak pressure-induced injury due to its vulnerability.

Data from the Lovelace Foundation experiments show instances of GI tract contusions after exposures up to 1147 psi peak pressure, while exposures of up to 588 psi peak pressure resulted in many instances of no observed GI tract effects. As a vulnerable gas-containing organ, the GI tract is vulnerable to both high peak pressure and high impulse, which may vary to exposure geometry. This likely explains the range of effects seen at similar peak pressure exposure levels and shows the utility of dual injury criteria for explosives.

To account for injuries seen at lower exposures in the Lovelace data set, a peak pressure threshold of 104 psi (237 dB re 1 µPa peak) is used to estimate injury in addition to the impulse injury threshold.

REFERENCES

29 CFR 1910.95 (2008). “Occupational noise exposure,” in Occupational Safety and Health Standards (Office of Federal Register, Washington, DC).

Andersen, S. (1970). “Auditory sensitivity of the harbour porpoise *Phocoena phocoena*,” in Investigations on Cetaceans, edited by G. Pilleri (Berne, Switzerland), pp. 255-259.

Antunes, R., Kvadsheim, P. H., Lam, F. P., Tyack, P. L., Thomas, L., Wensveen, P. J., and Miller, P. J. (2014). High thresholds for avoidance of sonar by free-ranging long-finned pilot whales (*Globicephala melas*). Marine Pollution Bulletin, 83(1), 165–180.

Awbrey, F.T., Thomas, J.A., and Kastelein, R.A. (1988). “Low-frequency underwater hearing sensitivity in belugas, *Delphinapterus leucas*,” Journal of the Acoustical Society of America 84, 2273-2275.

Babushina, E.S. (1997). “Audiograms of the Caspian seal under water and in air,” Sensory Systems 11, 67-71.

Babushina, Y.S., Zaslavskii, G.L., and Yurkevich, L.I. (1991). “Air and underwater hearing characteristics of the northern fur seal: audiograms, frequency and differential thresholds,” Biophysics 36, 909-913.

Baird, R.W., Cornforth, C.J., Jarvis, S.M., DiMarzio, N.A., Dolan, K., Henderson, E.E., Martin, S.W., Watwood, S.L., Mahaffy, S.D., Guenther, B.D., Lerma, J.K., Harnish, A.E., and Kratofil, M.A. (2021). “Odontocete studies on the Pacific Missile Range Facility in February 2020: satellite tagging, photo-identification, and passive acoustic monitoring,” Pearl Harbor, HI. Naval Facilities Engineering Command (NAVFAC) Pacific. Contract No. N62470-15-D-8006 Task Order N6274219F0101.

Barlow, J., and Gisiner, R. (2006). Mitigating, monitoring and assessing the effects of anthropogenic sound on beaked whales. Journal of Cetacean Research and Management, 7(3), 239–249.

Bartol, S. M. and Ketten, D. R. (2006). Turtle and Tuna Hearing (NOAA Technical Memorandum NMFS-PIFSC-7). Honolulu, HI: National Oceanic and Atmospheric Administration, National Marine Fisheries Service, Pacific Islands Fisheries Science Center.

Blackwell, S. B., Lawson, J. W., and Williams, M. T. (2004). Tolerance by ringed seals (*Phoca hispida*) to impact pipe-driving and construction sounds at an oil production island. The Journal of the Acoustical Society of America, 115(5), 2346-2357.

Blackwell, S. B., Nations, C. S., McDonald, T. L., Greene Jr, C. R., Thode, A. M., Guerra, M., and Michael Macrander, A. (2013). Effects of airgun sounds on bowhead whale calling rates in the Alaskan Beaufort Sea. Marine Mammal Science, 29(4), E342-E365.

Blackwell, S. B., Nations, C. S., McDonald, T. L., Thode, A. M., Mathias, D., Kim, K. H., Charles, R. G., and Macrander, A. M. (2015). Effects of airgun sounds on bowhead whale calling rates: evidence for two behavioral thresholds. PloS one, 10(6), e0125720.

Boisseau, O., McGarry, T., Stephenson, S., Compton, R., Cucknell, A.-C., Ryan, C., McLanaghan, R., and Moscrop, A. (2021). “Minke whales *Balaenoptera acutorostrata* avoid a 15 kHz acoustic deterrent device (ADD),” Marine Ecology Progess Series 667, 191-206.

Bouchet P.J., Harris, C.M., and Thomas, L. (2020). Simulating cetacean responses to sonar exposure within a Bayesian hierarchical modelling framework. CREEM Technical Report 2020-01, University of St Andrews.

Bouchet, P.J., Harris, C.M., and Thomas, L. (2021). Assessing the role of uncertainty in received sound levels for predicting behavioural responses of cetaceans exposed to naval sonar. Frontiers in Marine Science 8: 674554.

Bowen, I. G., Fletcher, E. R., Richmond, D. R., Hirsch, F. G., and White, C. S. (1968). Biophysical mechanisms and scaling procedures applicable in assessing responses of the thorax energized by air-blast overpressures or by non-penetrating missiles. Annals of the New York Academy of Sciences 152 (1): 122–146.

Bowles, A. E., and Anderson, R. C. (2012). Behavioral responses and habituation of pinnipeds and small cetaceans to novel objects and simulated fishing gear with and without a pinger. Aquatic Mammals, 38(2), 161.

Boyd, I. L., Tyack, P. L., Claridge, D., Clark, C., Moretti, D., and Southall, B. L. (2009). Behavioural Response Study. Paper presented at the 2009 ONR Marine Mammal Program Review, Alexandria, VA.

Brandt, M. J., Diederichs, A., Betke, K., and Nehls, G. (2011). Responses of harbour porpoises to pile driving at the Horns Rev II offshore wind farm in the Danish North Sea. Marine Ecology Progress Series, 421, 205-216.

Brandt, M. J., Dragon, A. C., Diederichs, A., Schubert, A., Kosarev, V., Nehls, G., and Piper, W. (2016). Effects of offshore pile driving on harbour porpoise abundance in the German Bight. Assessment of noise effects. Report by BioConsult SH, IBL Umweltplanung GmbH, and Institute of Applied Ecology (IfAO).

Branstetter, B.K., St. Leger, J., Acton, D., Stewart, J., Houser, D., Finneran, J.J., and Jenkins, K. (2017). “Killer whale (*Orcinus orca*) behavioral audiograms,” J. Acoust. Soc. Am. 141, 2387-2398.

Brill, R.L., Moore, P.W.B., and Dankiewicz, L.A. (2001). “Assessment of dolphin (*Tursiops truncatus*) auditory sensitivity and hearing loss using jawphones,” Journal of the Acoustical Society of America 109, 1717-1722.

Brooks, S. P. and Gelman, A. (1998). General methods for monitoring convergence of iterative simulations. Journal of Computational and Graphical Statistics 7 (4): 434–455.

Buck, J. R., and Tyack, P. L. (2000). Response of gray whales to low-frequency sounds. Journal of the Acoustical Society of America, 107(5), 2774.

Carstensen, J., Henriksen, O. D., and Teilmann, J. (2006). Impacts of offshore wind farm construction on harbour porpoises: acoustic monitoring of echolocation activity using porpoise detectors (T-PODs). Marine Ecology Progress Series, 321, 295-308.

Christensen-Dalsgaard, J., Brandt, C., Willis, K. L., Christensen, C. B., Keeten, D., Edds-Walton, P. L., and Fay, R. R. (2012). Specialization for underwater hearing by the tympanic middle ear of the turtle, *Trachemy scripta elegans*. Proceeding of the Royal Society of Biology 279 (1739): 2816–2824. DOI:10.1098/rspb.2012.0290

Christian, E. A. and Gaspin, J. B. (1974). Swimmer Safe Standoffs from Underwater Explosions. Navy Science Assistance Program Project No. PHP-11-73. White Oak, MD: Naval Ordnance Laboratory.

Christiansen, F., Rasmussen, M., and Lusseau, D. (2013). Whale watching disrupts feeding activities of minke whales on a feeding ground. Marine Ecology Progress Series 478 239–251. DOI:10.3354/meps10163

Clark, C. W., and Fristrup, K. M. (2001). Baleen whale responses to low-frequency human-made underwater sounds. Journal of the Acoustical Society of America, 110(5), 2751.

Clark, C. W., Tyack, P. L., and Ellison, W. T. (1999). Technical Report 1: Low Frequency Sound Scientific Research Program Technical Report on Responses for Four Species of Whales to Sounds of SURTASS LFA Sonar Transmissions (Overseas Environmental Impact Statement and Environmental Impact Statement for Surveillance Towed Array Sensor System Low Frequency Active (SURTASS LFA) Sonar).

Cook, M. (2006). “Behavioral and Auditory Evoked Potential (AEP) Hearing Measurements in Odontocete Cetaceans,” University of South Florida (Ph.D.). pp.

Cranford, T. W., and P. Krysl. (2015). Fin whale sound reception mechanisms: Skull vibration enables low-frequency hearing. PLoS ONE 10 (1): e0116222. DOI:10.1371/journal.pone.0116222

Croll, D. A., C. W., Clark, J., Calambokidis, W. T. Ellison, and B. R. Tershy. (2001). Effect of anthropogenic low-frequency noise on the foraging ecology of Balaenoptera whales. Animal Conservation, 4, 13–27.

Cudahy, E. and S. Parvin. (2001). The Effects of Underwater Blast on Divers. Groton, CT: Naval Submarine Medical Research Laboratory.

Cunningham, K.A. and Reichmuth, C. (2016). “High-frequency hearing in seals and sea lions,” Hear. Res. 331, 83-91.

Curé, C., Isojunno, S., Siemensma, M.L., Wensveen, P.J., Buisson, C., Sivle, L.D., Benti, B., Roland, R., Kvadsheim, P.H., Lam, F.P.A. and Miller, P.J. (2021). Severity Scoring of Behavioral Responses of Sperm Whales (*Physeter macrocephalus*) to Novel Continuous versus Conventional Pulsed Active Sonar. Journal of Marine Science and Engineering, 9(4), p.444.

Dähne, M., Gilles, A., Lucke, K., Peschko, V., Adler, S., Krügel, K., Sundermeyer, J. and Siebert, U. (2013). Effects of pile-driving on harbour porpoises (*Phocoena phocoena*) at the first offshore wind farm in Germany. Environmental Research Letters, 8(2), p.025002.

Dähne, M., V. Peschko, A. Gilles, K. Lucke, S. Adler, K. Ronnenberg, and U. Siebert. (2014). Marine mammals and windfarms: effects of alpha ventus on harbour porpoises Ecological Research at the Offshore Windfarm alpha ventus (pp. 133–149). Springer.

D'Amico, A., R. C. Gisiner, D. R. Ketten, J. A. Hammock, C. Johnson, P. L. Tyack, and J. Mead. (2009). Beaked whale strandings and naval exercises. Aquatic Mammals, 35(4), 452–472.

Danil, K. and J. A. St. Ledger. (2011). Seabird and dolphin mortality associated with underwater detonation exercises. Marine Technology Society Journal 45 (6): 63–87.

DeRuiter, S. L. and K. L. Doukara. (2012). Loggerhead turtles dive in response to airgun sound exposure. Endangered Species Research 16 (1): 55–63. DOI:10.3354/esr00396

DeRuiter, S. L., S. B. L., J. Calambokidis, W. M. X. Zimmer, D. Sadykova, E. A. Falcone, A. S. Friedlaender, J. E. Joseph, D. Moretti, G. S. Schorr, L. Thomas, and P. L. Tyack. (2013). First direct measurements of behavioral responses by Cuvier’s beaked whales to mid-frequency active sonar. Biology Letters, 9, 201–223.

Di Iorio, L., and Clark, C. W. (2009). Exposure to seismic survey alters blue whale acoustic communication. Biology letters, 6(1), 51-54.

Dunlop, R. A., Noad, M. J., Cato, D. H., Kniest, E., Miller, P. J., Smith, J. N., and Stokes, M. D. (2013). Multivariate analysis of behavioral response experiments in humpback whales (*Megaptera novaeangliae*). Journal of Experimental Biology, 216(5), 759-770.

Dunlop, R. A., Noad, M. J., McCauley, R. D., Kniest, E., Slade, R., Paton, D., and Cato, D. H. (2016). Response of humpback whales (*Megaptera novaeangliae*) to ramp-up of a small experimental air gun array. Marine pollution bulletin, 103(1-2), 72-83.

Dunlop, R. A., Noad, M. J., McCauley, R. D., Scott-Hayward, L., Kniest, E., Slade, R., and Cato, D. H. (2017). Determining the behavioral dose–response relationship of marine mammals to air gun noise and source proximity. Journal of Experimental Biology, 220(16), 2878-2886.

Dunn, R. A., and Hernandez, O. (2009). Tracking blue whales in the eastern tropical Pacific with an ocean-bottom seismometer and hydrophone array. The Journal of the Acoustical Society of America, 126(3), 1084-1094.

Durbach, I. N., Harris, C. M., Martin, C., Helble, T. A., Henderson, E. E., Ierley, G., Thomas, L., and Martin, S. W. (2021). Changes in the movement and calling behavior of minke whales (Balaenoptera acutorostrata) in response to navy training. Frontiers in Marine Science, 8, 660122.

Durban, J.W., Southall, B.L., Calambokidis, J., Casey, C., Fearnbach, H., Joyce, T.W., Fahlbusch, J.A., Oudejans, M.G., Fregosi, S., Friedlaender, A.S. and Kellar, N.M. (2022). Integrating remote sensing methods during controlled exposure experiments to quantify group responses of dolphins to navy sonar. Marine pollution bulletin, 174, p.113194.

Edrén, S. M., Andersen, S. M., Teilmann, J., Carstensen, J., Harders, P. B., Dietz, R., and Miller, L. A. (2010). The effect of a large Danish offshore wind farm on harbor and gray seal haul-out behavior. Marine Mammal Science, 26(3), 614-634.

Ellison, W. T., B. L. Southall, C. W. Clark, and A. S. Frankel. (2011). A new context-based approach to assess marine mammal behavioral responses to anthropogenic sounds. Conservation Biology, 26(1), 21–28.

Fahlman, A., S. K. Hooker, A. Olszowka, B. L. Bostrom, and D. R. Jones. (2009). Estimating the effect of lung collapse and pulmonary shunt on gas exchange during breath-hold diving: The Scholander and Kooyman legacy. Respiratory Physiology and Neurobiology 165 (1): 28–39. DOI:10.1016/j.resp.2008.09.013

Falcone, E. A., Schorr, G. S., Watwood, S. L., DeRuiter, S. L., Zerbini, A. N., Andrews, R. D., Morrissey, R.P., and Moretti, D. J. (2017). Diving behaviour of Cuvier's beaked whales exposed to two types of military sonar. Royal Society Open Science, 4(8), 170629.

Falke, K. J., R. D. Hill, J. Qvist, R. C. Schneider, M. Guppy, G. C. Liggins, P. W. Hochachka, R. E. Elliott, and W. M. Zapol. (1985). Seal lungs collapse during free diving: Evidence from arterial nitrogen tensions. Science 229, 556–558.

Fernandez, K. A., P. W. Jeffers, K. Lall, M. C. Liberman, and S. G. Kujawa. (2015). Aging after noise exposure: acceleration of cochlear synaptopathy in "recovered" ears. Journal of Neuroscience 35 (19): 7509-7520. DOI:10.1523/JNEUROSCI.5138-14.2015

Finneran, J. J. (2015). Noise-induced hearing loss in marine mammals: A review of temporary threshold shift studies from 1996 to 2015. The Journal of the Acoustical Society of America 138 (3): 1702-1726.

Finneran, J. J. and A. K. Jenkins. (2012). Criteria and Thresholds for U.S. Navy Acoustic and Explosive Effects Analysis. San Diego, CA: SSC Pacific Technical Report.

Finneran, J. J. and C. E. Schlundt. (2004). Effects of Intense Pure Tones on the Behavior of Trained Odontocetes. SSC Pacific Technical Report.

Finneran, J. J. and C. E. Schlundt. (2007). Underwater sound pressure variation and bottlenose dolphin (*Tursiops truncatus*) hearing thresholds in a small pool. Journal of the Acoustical Society of America, 122, 606-614.

Finneran, J. J. and C. E. Schlundt. (2013). Effects of fatiguing tone frequency on temporary threshold shift in bottlenose dolphins (*Tursiops truncatus*). Journal of the Acoustical Society of America, 133, 1819-1826.

Finneran, J. J., C. E. Schlundt, D. A. Carder, J. A. Clark, J. A. Young, J. B. Gaspin, and S. H. Ridgway. (2000). Auditory and behavioral responses of bottlenose dolphins (*Tursiops truncatus*) and a beluga whale (*Delphinapterus leucas*) to impulsive sounds resembling distant signatures of underwater explosions. Journal of the Acoustical Society of America, 108(1), 417-431.

Finneran, J.J., Schlundt, C.E., Dear, R., Carder, D.A., and Ridgway, S.H. (2002). "Temporary shift in masked hearing thresholds (MTTS) in odontocetes after exposure to single underwater impulses from a seismic watergun," Journal of the Acoustical Society of America 111, 2929-2940.

Finneran, J. J., R. Dear, D. A. Carder, and S. H. Ridgway. (2003). Auditory and behavioral responses of California sea lions (*Zalophus californianus*) to single underwater impulses from an arc-gap transducer. Journal of the Acoustical Society of America 114 (3): 1667-1677.

Finneran, J. J., Carder, D. A., Schlundt, C. E., and Ridgway, S. H. (2005a). Temporary threshold shift in bottlenose dolphins (*Tursiops truncatus*) exposed to mid-frequency tones. The Journal of the Acoustical Society of America, 118(4), 2696-2705.

Finneran, J.J., Carder, D.A., Dear, R., Belting, T., McBain, J., Dalton, L., and Ridgway, S.H. (2005b). "Pure tone audiograms and possible aminoglycoside-induced hearing loss in belugas (*Delphinapterus leucas*)," Journal of the Acoustical Society of America 117, 3936-3943.

Finneran, J. J., C. E. Schlundt, B. Branstetter, and R. L. Dear. (2007). Assessing temporary threshold shift in a bottlenose dolphin (Tursiops truncatus) using multiple simultaneous auditory evoked potentials. The Journal of the Acoustical Society of America 122 (2): 1249–1264. DOI:10.1121/1.2749447

Finneran, J. J., D. A. Carder, C. E. Schlundt, and R. L. Dear. (2010a). Growth and recovery of temporary threshold shift (TTS) at 3 kHz in bottlenose dolphins (*Tursiops truncatus*). Journal of the Acoustical Society of America 127 (5): 3256-3266.

Finneran, J.J., Carder, D.A., Schlundt, C.E., and Dear, R.L. (2010b). "Temporary threshold shift in a bottlenose dolphin (*Tursiops truncatus*) exposed to intermittent tones," Journal of the Acoustical Society of America 127, 3267-3272.

Finneran, J. J., C. E. Schlundt, B. K. Branstetter, J. S. Trickey, V. Bowman, and K. Jenkins. (2015). Effects of multiple impulses from a seismic air gun on bottlenose dolphin hearing and behavior. The Journal of Acoustical Society of America, 137(4), 1634–1646.

Finneran, J. J., C. E. Schlundt, and J. Mulsow. (2023). Temporary threshold shift in bottlenose dolphins exposed to steady-state, 1/6-octave noise centered at 0.5 to 80 kHz). Journal of the Acoustic Society of America 154 (2): 1324-1338. DOI:10.1121/10.0020728

Ford, J. K. B., and H. D. Fisher. (1982). Killer whale (*Orcinus orca*) dialects as an indicator of stocks in British Columbia. Reports of the International Whaling Commission, 32, 671-679.

Frankel, A. S., and Stein, P. J. (2020). Gray whales hear and respond to signals from a 21–25 kHz active sonar. Marine Mammal Science, 36(4), 1111-1125.

Fristrup, K. M., L. T. Hatch, and C. W. Clark. (2003). Variation in humpback whale (*Megaptera novaeangliae*) song length in relation to low-frequency sound broadcasts. The Journal of Acoustical Society of America, 113(6), 3411–3424.

Fromm, D. M. (2009). Reconstruction of Acoustic Exposure on Orcas in Haro Strait (Acoustics).

Gailey, G., Sychenko, O., McDonald, T., Racca, R., Rutenko, A., and Bröker, K. (2016). Behavioral responses of western gray whales to a 4-D seismic survey off northeastern Sakhalin Island, Russia. Endangered species research, 30, 53-71.

Gaspard, J.C., III, Bauer, G.B., Reep, R.L., Dziuk, K., Cardwell, A., Read, L., and Mann, D.A. (2012). “Audiogram and auditory critical ratios of two Florida manatees (*Trichechus manatus latirostris*),” Journal of Experimental Biology 215, 1442-1447.

Gerstein, E.R., Gerstein, L., Forsythe, S.E., and Blue, J.E. (1999). “The underwater audiogram of the West Indian manatee (*Trichechus manatus*),” Journal of the Acoustical Society of America 105, 3575-3583.

Ghoul, A. and Reichmuth, C. (2014). “Hearing in the sea otter (*Enhydra lutris*): auditory profiles for an amphibious marine carnivore,” Journal of Comparative Physiology A 200, 967-981.

Goertner, J. F. (1982). Prediction of Underwater Explosion Safe Ranges for Sea Mammals. Dahlgren, VA: Naval Surface Weapons Center.

Goldbogen, J. A., Southall, B. L., DeRuiter, S. L., Calambokidis, J., Friedlaender, A. S., Hazen, E. L., Falcone, E. A., Schorr, G. S., Douglas, A., Moretti, D. J., Kyburg, C., McKenna, M. F., and P. L. Tyack. (2013). Blue whales respond to simulated mid-frequency military sonar. Proc Biol Sci, 280(1765), 20130657.

Götz, T. (2008). Aversiveness of sound in marine mammals: Psycho-physiological basis, behavioral correlates and potential applications. (PhD dissertation). University of St Andrews.

Götz, T., and Janik, V. M. (2011). Repeated elicitation of the acoustic startle reflex leads to sensation in subsequent avoidance behavior and induces fear conditioning. BMC Neuroscience, 12(30), 13.

Graham, I. M., Pirotta, E., Merchant, N. D., Farcas, A., Barton, T. R., Cheney, B., Hastie, G. D., and Thompson, P. M. (2017). Responses of bottlenose dolphins and harbor porpoises to impact and vibration piling noise during harbor construction. Ecosphere, 8(5), e01793.

Hall, J.D. and Johnson, C.S. (1972). “Auditory thresholds of a killer whale *Orcinus orca* Linnaeus,” Journal of the Acoustical Society of America 51, 515-517.

Halvorsen, M. B., D. G. Zeddies, W. T. Ellison, D. R. Chicoine, and A. N. Popper. (2012). Effects of mid-frequency active sonar on hearing in fish. The Journal of the Acoustical Society of America 131 (1): 599–607.

Halvorsen, M. B., D. G. Zeddies, D. Chicoine, and A. N. Popper. (2013). Effects of low-frequency naval sonar exposure on three species of fish. The Journal of the Acoustical Society of America 134 (2): EL205–210. DOI:10.1121/1.4812818

Harris, C. M., Martin, S. W., Martin, C., Helble, T. A., Henderson, E. E., Paxton, C. G., and Thomas, L. (2019). Changes in the spatial distribution of acoustically derived minke whale (Balaenoptera acutorostrata) tracks in response to Navy training. Aquatic Mammals, 45(6).

Harris, R. E., Miller, G. W., and Richardson, W. J. (2001). Seal responses to airgun sounds during summer seismic surveys in the Alaskan Beaufort Sea. Marine Mammal Science, 17(4), 795-812.

Hastie, G., Merchant, N. D., Götz, T., Russell, D. J., Thompson, P., and Janik, V. M. (2019). Effects of impulsive noise on marine mammals: investigating range-dependent risk. Ecological Applications, 29(5), e01906.

Heffner, R. S., and Heffner, H. E. (1982). Hearing in the elephant (*Elephas maximus*): Absolute sensitivity, frequency discrimination, and sound localization. Journal of Comparative and Physiological Psychology 96 (6): 926–944.

Heffner, R. S., and Heffner, H. E. (1992). Evolution of sound localization in mammals. In The Evolutionary Biology of Hearing (pp. 691–715). New York, NY: Springer-Verlag.

Henderson, E. E., Smith, M. H., Gassmann, M., Wiggins, S. M., Douglas, A. B., and Hildebrand, J. A. (2014). Delphinid behavioral responses to incidental mid-frequency active sonar. The Journal of Acoustical Society of America, 136(4), 2003–2014.

Henderson, E. E., S. W. Martin, R. Manzano-Roth, and B. M. Matsuyama. (2016). Occurrence and habitat use of foraging Blainville's beaked whales (*Mesoplodon densirostris*) on a U.S. Navy range in Hawai'i. Aquatic Mammals, 42(4).

Henriksen, O. D., Teilmann, J., and Carstensen, J. (2003). Effects of the Nysted Offshore Wind Farm Construction on Harbour Porpoises–the 2002 Annual Status Report for the Acoustic T-POD Monitoring Programme. National Environmental Research Institute, Roskilde.

Hochscheid, S., C. R. McMahon, C. J. A. Bradshaw, F. Maffucci, F. Bentivegna, and G. C. Hays. (2007). Allometric scaling of lung volume and its consequences for marine turtle diving performance. Comparative Biochemistry and Physiology Part A: Molecular & Integrative Physiology 148 (2), 360–367.

Holt, M.M., Ghoul, A., and Reichmuth, C. (2012). “Temporal summation of airborne tones in a California sea lion (*Zalophus californianus*),” Journal of the Acoustical Society of America 132, 3569-3575.

Houser, D. S. (2021). When is temporary threshold shift injurious to marine mammals? Journal of Marine Science and Engineering 9 (757). DOI:10.3390/jmse9070757

Houser, D. S., D. A. Helweg, and P. W. B. Moore. (2001). A bandpass filter-bank model of auditory sensitivity in the humpback whale. Aquatic Mammals 27 (2), 82–91.

Houser, D. S., S. W. Martin, and J. J. Finneran. (2013a). Exposure amplitude and repetition affect bottlenose dolphin behavioral responses to simulated mid-frequency sonar signals. Journal of Experimental Marine Biology and Ecology, 443, 123–133.

Houser, D. S., S. W. Martin, and J. J. Finneran. (2013b). Behavioral responses of California sea lions to mid-frequency (3250-3450 Hz) sonar signals. Marine Environmental Research, 92, 268–278.

Houser, D. S., P. H. Kvadsheim, L. Kleivane, J. Mulsow, R. A. Ølberg, C. A. Harms, J. Teilmann, and J. J. Finneran. (2024). Direct hearing measurements in a baleen whale suggest ultrasonic sensitivity. Science, 386 (6724), 902 – 906. DOI:10.1126/science.ado7580

Isojunno, S., Wensveen, P. J., Lam, F. P. A., Kvadsheim, P. H., von Benda-Beckmann, A. M., Martín López, L. M., Kleivane, L., Siegal, E. M., and Miller, P. J. (2020). When the noise goes on: received sound energy predicts sperm whale responses to both intermittent and continuous navy sonar. Journal of Experimental Biology, 223(7), jeb219741.

Isojunno, S., von Benda-Beckmann, A.M., Wensveen, P.J., Kvadsheim, P.H., Lam, F.P.A., Gkikopoulou, K.C., Pöyhönen, V., Tyack, P.L., Benti, B., Foskolos, I. and Bort, J. (2021). Sperm whales exhibit variation in echolocation tactics with depth and sea state but not naval sonar exposures. Marine Mammal Science.

Jacobs, D.W. and Hall, J.D. (1972). “Auditory thresholds of a fresh water dolphin, *Inia geoffrensis* Blainville,” Journal of the Acoustical Society of America 51, 530-533.

Jacobs, S. R., and Terhune, J. (2002). The effectiveness of acoustic harassment devices in the Bay of Fundy, Canada: seal reactions and a noise exposure model. Aquatic Mammals, 28(2), 147-158.

Jacobson, E. K., E. E. Henderson, D. L. Miller, C. S. Oedekoven, D. J. Moretti, and L. Thomas. (2022). Quantifying the response of Blainville's beaked whales to U.S. naval sonar exercises in Hawaii. Marine Mammal Science. DOI:https://doi.org/10.1111/mms.12944

Jett, J., B. Thapa, and R. Sweet. (2013). Boater speed compliance in manatee zones: examining a proposed predictive model. Society and Natural Resources, 26, 95–104.

Johnson, C.S. (1967). “Sound detection thresholds in marine mammals,” in Marine Bioacoustics, edited by W.N. Tavolga (Pergamon Press, Oxford), pp. 247-260.

Johnson, C.S., McManus, M.W., and Skaar, D. (1989). “Masked tonal hearing thresholds in the beluga whale,” Journal of the Acoustical Society of America 85, 2651-2654.

Johnston, D. W. (2002). The effect of acoustic harassment devices on harbour porpoises (*Phocoena phocoena*) in the Bay of Fundy, Canada. Biological Conservation, 108, 113–118.

Joyce, T. W., Durban, J. W., Claridge, D. E., Dunn, C. A., Hickmott, L. S., Fearnbach, H., Dolan, K., and Moretti, D. (2020). Behavioral responses of satellite tracked Blainville's beaked whales (Mesoplodon densirostris) to mid-frequency active sonar. Marine Mammal Science, 36(1), 29-46.

Kastak, D. and Schusterman, R.J. (1998). “Low-frequency amphibious hearing in pinnipeds: Methods, measurements, noise, and ecology,” Journal of the Acoustical Society of America 103, 2216-2228.

Kastak, D. and Schusterman, R.J. (1999). “In-air and underwater hearing sensitivity of a northern elephant seal (*Mirounga angustirostris*),” Can. J. Zool. 77, 1751-1758.

Kastak, D. and Schusterman, R.J. (2002). “Changes in auditory sensitivity with depth in a free-diving California sea lion (*Zalophus californianus*),” Journal of the Acoustical Society of America 112, 329-333.

Kastak, D., B. L. Southall, R. J. Schusterman, and C. R. Kastak. (2005). Underwater temporary threshold shift in pinnipeds: Effects of noise level and duration. The Journal of the Acoustical Society of America 118 (5): 3154–3163. DOI:10.1121/1.2047128

Kastak, D., C. Reichmuth, M. M. Holt, J. Mulsow, B. L. Southall, and R. J. Schusterman. (2007). Onset, growth, and recovery of in-air temporary threshold shift in a California sea lion (*Zalophus californianus*). Journal of the Acoustical Society of America 122 (5): 2916–2924.

Kastelein, R. A., A. D. Goodson, D. de Haan, and J. Lien. (1995). The Effects of Acoustic Alarms on Harbour Porpoise (*Phocoena phocoena*) Behaviour. In P. E. Nachtigall, J. Lien, W. W. L. Au and A. J. Read (Eds.), Harbour porpoises: Laboratory Studies to Reduce Bycatch (pp. 157–167). Woerden, The Netherlands: De Spil Publishers.

Kastelein, R.A., Mosterd, P., van Ligtenberg, C.L., and Verboom, W.C. (1996). “Aerial hearing sensitivity tests with a male Pacific walrus (*Odobenus rosmarus divergens*), in the free field and with headphones.,” Aquat. Mammal. 22, 81-93.

Kastelein, R. A., H. T. Rippe, N. Vaughan, N. M. Schooneman, W. C. Verboom, and D. de Haan. (2000). The effects of acoustic alarms on the behavior of harbor porpoises (*Phocoena phocoena*) in a floating pen. Marine Mammal Science, 16(1), 46–64.

Kastelein, R.A., Mosterd, P., van Santen, B., Hagedoorn, M., and de Haan, D. (2002a). "Underwater audiogram of a Pacific walrus (*Odobenus rosmarus divergens*) measured with narrow-band frequency-modulated signals," Journal of the Acoustical Society of America 112, 2173-2182.

Kastelein, R.A., Bunskoek, P., Hagedoorn, M., Au, W.W.L., and de Haan, D. (2002b). "Audiogram of a harbor porpoise (*Phocoena phocoena*) measured with narrow-band frequency-modulated signals," Journal of the Acoustical Society of America 112, 334-344.

Kastelein, R.A., Hagedoorn, M., Au, W.W.L., and de Haan, D. (2003). "Audiogram of a striped dolphin (*Stenella coeruleoalba*)," Journal of the Acoustical Society of America 113, 1130-1137.

Kastelein, R.A., van Schie, R., Verboom, W.C., and de Haan, D. (2005). "Underwater hearing sensitivity of a male and a female Steller sea lion (*Eumetopias jubatus*)," Journal of the Acoustical Society of America 118, 1820-1829.

Kastelein, R., N. Jennings, W. Verboom, D. de Haan, and N. M. Schooneman. (2006a). Differences in the response of a striped dolphin (*Stenella coeruleoalba*) and a harbor porpoise (*Phocoena phocoena*) to an acoustic alarm. Marine Environmental Research, 61, 363–378.

Kastelein, R. A., S. van der Heul, J. M. Terhune, W. C. Verboom, and R. J. V. Triesscheijn. (2006b). Deterring effects of 8-45 kHz tone pulses on harbour seals (*Phoca vitulina*) in a large pool. Marine Environmental Research, 62, 356–373.

Kastelein, R. A., van der Heul, S., Verboom, W. C., Triesscheijn, R. J. V., and Jennings. N.J. (2006c). The influence of underwater data transmission sounds on the displacement behaviour of captive harbour seals (*Phoca vitulina*). Marine Environmental Research, 61: 19-39.

Kastelein, R. A., W. C. Verboom, N. Jennings, and D. de Haan. (2008). Behavioral avoidance threshold level of a harbor porpoise (*Phocoena phocoena*) for a continuous 50 kHz pure tone (L). Journal of the Acoustical Society of America, 123(4), 1858–1861.

Kastelein, R.A., Wensveen, P., Hoek, L., and Terhune, J.M. (2009a). "Underwater hearing sensitivity of harbor seals (*Phoca vitulina*) for narrow noise bands between 0.2 and 80 kHz," Journal of the Acoustical Society of America 126, 476–483.

Kastelein, R.A., Wensveen, P.J., Hoek, L., Verboom, W.C., and Terhune, J.M. (2009b). "Underwater detection of tonal signals between 0.125 and 100 kHz by harbor seals (*Phoca vitulina*)," Journal of the Acoustical Society of America 125, 1222-1229.

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

Kastelein, R.A., Gransier, R., Hoek, L., and Olthuis, J. (2012a). "Temporary threshold shifts and recovery in a harbor porpoise (*Phocoena phocoena*) after octave-band noise at 4 kHz," Journal of the Acoustical Society of America 132, 3525-3537.

Kastelein, R.A., Gransier, R., Hoek, L., Macleod, A., and Terhune, J.M. (2012b). "Hearing threshold shifts and recovery in harbor seals (*Phoca vitulina*) after octave-band noise exposure at 4 kHz," Journal of the Acoustical Society of America 132, 2745-2761.

Kastelein, R.A., Gransier, R., and Hoek, L. (2013a). “Comparative temporary threshold shifts in a harbor porpoise and harbor seal, and severe shift in a seal,” Journal of the Acoustical Society of America 134, 13-16.

Kastelein, R.A., Gransier, R., Hoek, L., and Rambags, M. (2013b). “Hearing frequency thresholds of a harbor porpoise (*Phocoena phocoena*) temporarily affected by a continuous 1.5 kHz tone,” Journal of the Acoustical Society of America 134, 2286-2292.

Kastelein, R. A., D. van Heerden, R. Gransier, and L. Hoek. (2013c). Behavioral responses of a harbor porpoise (*Phoceoena phocoena*) to playbacks of broadband pile driving sounds. Marine Environmental Research, 92, 206–214.

Kastelein, R. A., Steen, N., Gransier, R., and De Jong, C. A. (2013d). Brief behavioral response threshold level of a harbor porpoise (*Phocoena phocoena*) to an impulsive sound. Aquatic Mammals, 39(4).

Kastelein, R. A., Gransier, R., van den Hoogen, M., and Hoek, L. (2013e). Brief behavioral response threshold levels of a harbor porpoise (*Phocoena phocoena*) to five helicopter dipping sonar signals (1.33 to 1.43 kHz). Aquatic Mammals, 39(2), 162–173.

Kastelein, R.A., Schop, J., Gransier, R., and Hoek, L. (2014a). “Frequency of greatest temporary hearing threshold shift in harbor porpoises (*Phocoena phocoena*) depends on the noise level,” J. Acoust. Soc. Am. 136, 1410-1418.

Kastelein, R. A., Hoek, L., Gransier, R., Rambags, M., and Claeys, N. (2014b). Effect of level, duration, and inter-pulse interval of 1–2 kHz sonar signal exposures on harbor porpoise hearing. The Journal of the Acoustical Society of America, 136(1), 412-422.

Kastelein, R.A., Gransier, R., Schop, J., and Hoek, L. (2015a). “Effects of exposure to intermittent and continuous 6–7 kHz sonar sweeps on harbor porpoise (*Phocoena phocoena*) hearing,” J. Acoust. Soc. Am. 137, 1623-1633.

Kastelein, R.A., Gransier, R., Marijt, M.A.T., and Hoek, L. (2015b). “Hearing frequency thresholds of harbor porpoises (*Phocoena phocoena*) temporarily affected by played back offshore pile driving sounds,” J. Acoust. Soc. Am. 137, 556-564.

Kastelein, R.A., Schop, J., Hoek, L., and Covi, J. (2015c). “Hearing thresholds of a harbor porpoise (*Phocoena phocoena*) for narrow-band sweeps,” J. Acoust. Soc. Am. 138, 2508-2512.

Kastelein, R. A., I. van den Belt, R. Gransier, and T. Johansson. (2015d). Behavioral responses of a harbor porpoise (*Phocoena phocoena*) to 25.5- to 24.5-kHz sonar down-sweeps with and without side bands. Aquatic Mammals, 41(4), 400–411.

Kastelein, R. A., I. van den Belt, L. Helder-Hoek, R. Gransier, and T. Johansson. (2015e). Behavioral responses of a harbor porpoise (*Phocoena phocoena*) to 25-kHz FM sonar signals. Aquatic Mammals, 41(3), 311–326.

Kastelein, R. A., L. Helder-Hoek, G. Janssens, R. Gransier, and T. Johansson. (2015f). Behavioral responses of harbor seals (*Phoca vitulina*) to sonar signals in the 25-kHz range. Aquatic Mammals, 41(4), 388–399.

Kastelein, R. A., Hoek, L., Gransier, R., de Jong, C. A., Terhune, J. M., and Jennings, N. (2015g). Hearing thresholds of a harbor porpoise (*Phocoena phocoena*) for playbacks of seal scarer signals, and effects of the signals on behavior. Hydrobiologia, 756(1), 89-103.

Kastelein, R. A., Helder-Hoek, L., Gransier, R., Terhune, J. M., Jennings, N., and de Jong, C. A. (2015h). Hearing thresholds of harbor seals (*Phoca vitulina*) for playbacks of seal scarer signals, and effects of the signals on behavior. Hydrobiologia, 756(1), 75-88.

Kastelein, R. A., L. Helder-Hoek, J. Covi, and R. Gransier. (2016). Pile driving playback sounds and temporary threshold shift in harbor porpoises (*Phocoena phocoena*): Effect of exposure duration. The Journal of the Acoustical Society of America 139 (5): 2842-2851.

Kastelein, R.A., Helder-Hoek, L., and Voorde, S.V.d. (2017a). "Hearing thresholds of a male and a female harbor porpoise (*Phocoena phocoena*)," J. Acoust. Soc. Am. 142, 1006-1010.

Kastelein, R.A., Helder-Hoek, L., and Voorde, S.V.d. (2017b). "Effects of exposure to sonar playback sounds (3.5 – 4.1 kHz) on harbor porpoise (*Phocoena phocoena*) hearing," J. Acoust. Soc. Am. 142, 1965-1975.

Kastelein, R.A., Helder-Hoek, L., Voorde, S.V.d., Benda-Beckmann, A.M.v., Lam, F.-P.A., Jansen, E., Jong, C.A.F.d., and Ainslie, M.A. (2017c). "Temporary hearing threshold shift in a harbor porpoise (*Phocoena phocoena*) after exposure to multiple airgun sounds," J. Acoust. Soc. Am. 142, 2430-2442.

Kastelein, R. A., Huybrechts, J., Covi, J., and Helder-Hoek, L. (2017d). Behavioral Responses of a Harbor Porpoise (*Phocoena phocoena*) to Sounds from an Acoustic Porpoise Deterrent. Aquatic Mammals, 43(3).

Kastelein, R. A., Horvers, M., Helder-Hoek, L., Van de Voorde, S., ter Hofstede, R., and van der Meij, H. (2017e). Behavioral Responses of Harbor Seals (*Phoca vitulina*) to FaunaGuard Seal Module Sounds at Two Background Noise Levels. Aquatic Mammals, 43(4).

Kastelein, R. A., L. Helder-Hoek, A. Kommeren, J. Covi, and R. Gransier. (2018a). Effect of pile-driving sounds on harbor seal (*Phoca vitulina*) hearing. The Journal of the Acoustical Society of America 143 (6): 3583-3594. DOI:10.1121/1.5040493

Kastelein, R. A., Helder-Hoek, L., Van de Voorde, S., de Winter, S., Janssen, S., and Ainslie, M. A. (2018b). Behavioral Responses of Harbor Porpoises (*Phocoena phocoena*) to Sonar Playback Sequences of Sweeps and Tones (3.5-4.1 kHz). Aquatic Mammals 44(4), 389-404.

Kastelein, R.A., Helder-Hoek, L., and Gransier, R. (2019a). "Frequency of greatest temporary hearing threshold shift in harbor seals (*Phoca vitulina*) depends on fatiguing sound level," J. Acoust. Soc. Am. 145, 1353-1362.

Kastelein, R.A., Helder-Hoek, L., Cornelisse, S., Huijser, L.A.E., and Terhune, J.M. (2019b). "Temporary hearing threshold shift in harbor seals (*Phoca vitulina*) due to a one-sixth-octave noise band centered at 16 kHz," J. Acoust. Soc. Am. 146, 3113-3122.

Kastelein, R.A., Helder-Hoek, L., van Kester, R., Huisman, R., and Gransier, R. (2019c). "Temporary hearing threshold shift in harbor porpoises (*Phocoena phocoena*) due to one-sixth octave noise band at 16 kHz," Aquat. Mammal. 45, 280-292.

Kastelein, R.A., Helder-Hoek, L., Cornelisse, S., Huijser, L.A.E., and Gransier, R. (2019d). "Temporary hearing threshold shift in harbor porpoises (*Phocoena phocoena*) due to one-sixth-octave noise band at 32 kHz," Aquat. Mammal. 45, 549-562.

Kastelein, R. A., Verhoeven, A., and Helder-Hoek, L. (2019e). Behavioral Responses of a Harbor Porpoise (*Phocoena phocoena*) to a Series of Four Different Simulated Low-Frequency Sonar Sounds (1.33-1.43 kHz). Aquatic Mammals 45(6): 632-645.

Kastelein, R.A., Cornelisse, S.A., Huijser, L.A., and Helder-Hoek, L. (2020a). “Temporary hearing threshold shift in harbor porpoises (*Phocoena phocoena*) due to one-sixth-octave noise bands at 63 kHz,” Aquat. Mammal. 46, 167–182.

Kastelein, R.A., Helder-Hoek, L., Cornelisse, S.A., Huijser, L.A.E., and Terhune, J.M. (2020b). “Temporary hearing threshold shift in harbor seals (*Phoca vitulina*) due to a one-sixth-octave noise band centered at 32 kHz,” J. Acoust. Soc. Am. 147, 1885-1896.

Kastelein, R.A., Helder-Hoek, L., Cornelisse, S.A., Huijser, L.A.E., and Gransier, R. (2020c). “Temporary hearing threshold shift at ecololgically relevant frequencies in a harbor porpoise (*Phocoena phocoena*) due to exposure to a noise band centered at 88.4 kHz,” Aquat. Mammal. 46, 444-453.

Kastelein, R.A., Helder-Hoek, L., Cornelisse, S.A., Defiller, L.N., and Huijser, L.A.E. (2020d). “Temporary threshold shift in a second harbor porpoise (*Phocoena phocoena*) after exposure to a one-sixth-octave noise band at 1.5 kHz and a 6.5 kHz continuous wave,” Aquat. Mammal. 46, 431-443.

Kastelein, R.A., Parlog, C., Helder-Hoek, L., Cornelisse, S.A., Huijser, L.A.E., and Terhune, J.M. (2020e). “Temporary hearing threshold shift in harbor seals (*Phoca vitulina*) due to a one-sixth-octave noise band centered at 40 kHz,” J. Acoust. Soc. Am. 147, 1966-1976.

Kastelein, R.A., Helder-Hoek, L., Cornelisse, S.A., Defillet, L.N., Huijser, L.A.E., and Terhune, J.M. (2020f). “Temporary hearing threshold shift in harbor seals (*Phoca vitulina*) due to one-sixth-octave noise bands centered at 0.5, 1, and 2 kHz,” J. Acoust. Soc. Am. 148, 3873-3885.

Kastelein, R.A., Helder-Hoek, L., Cornelisse, S.A., von Benda-Beckmann, A.M., Lam, F.-P.A., de Jong, C.A.F., and Ketten, D.R. (2020g). “Lack of reproducibility of temporary hearing threshold shifts in a harbor porpoise after exposure to repeated airgun sounds,” J. Acoust. Soc. Am. 148, 556-565.

Kastelein, R.A., Helder-Hoek, L., Cornelisse, S.A., Defillet, L.N., Huijser, L.A.E., and Gransier, R. (2021a). “Temporary hearing threshold shift in a harbor porpoise (*Phocoena phocoena*) due to exposure to a continuous one-sixth-octave noise band centered at 0.5 kHz,” Aquat. Mammal. 47, 135–145.

Kastelein, R. A., L. Helder-Hoek, L. N. Defillet, L. A. E. Huijser, J. M. Terhune, and R. Gransier. (2021b). Temporary hearing threshold shift in California Sea Lions (*Zalophus californianus*) due to one-sixth-octave noise bands centered at 2 and 4 kHz: Effect of duty cycle and testing the equal-energy hypothesis. Aquatic Mammals 47 (4): 394–418. DOI:10.1578/AM.47.4.2021.394

Kastelein, R.A., Helder-Hoek, L., Defillet, L.N., Kuiphof, F., Huijser, L.A.E., and Terhune, J.M. (2022a). “Temporary hearing threshold shift in California sea lions (*Zalophus californianus*) due to one-sixth-octave noise bands centered at 8 and 16 kHz: Effect of duty cycle and testing the equal-energy hypothesis,” Aquat. Mammal. 48, 36-58.

Kastelein, R.A., Helder-Hoek, L., Defillet, L.N., Kuiphof, F., Huijser, L.A.E., and Terhune, J.M. (2022b). “Temporary hearing threshold shift in California sea lions (*Zalophus californianus*) due to one-sixth-octave noise bands centered at 0.6 and 1 kHz,” Aquat. Mammal. 48, 248-265.

Kastelein, R.A., Helder-Hoek, L., Van Acoleyen, L., Defillet, L., Huijser, L.A.E., and Terhune, J.M. (2023a). “Underwater sound detection thresholds (0.031-80 kHz) of two California sea lions (*Zalophus californianus*) and a revised generic audiogram for the species,” Aquat. Mammal. (in review).

Kastelein, R. A., A. Smink, and N. Jennings. (2023b). Atlantic Green Turtles and Hawksbill Turtles: Behavioral Responses to Sound. In A. N. Popper, Sisneros, J., Hawkins, A.D., Thomsen, F. (Ed.), The Effects of Noise on Aquatic Life. Cham, Switzerland: Springer, Cham.

Kastelein, R.A., Helder-Hoek, L., Defillet, L.N., Kuiphof, F., Huijser, L.A.E., and Terhune, J.M. (2024). “Temporary hearing threshold shift in California sea lions (*Zalophus californianus*) due to one-sixth-octave noise bands centered at 32 kHz,” Aquat. Mammal. (in prep).

Ketten, D. R. (1994). Functional analyses of whale ears: Adaptations for underwater hearing. Presented at the IEEE Proceedings in Underwater Acoustics, pp. 264-270. Brest, France.

Ketten, D. R. (2000). Cetacean Ears. In W. Au, A. N. Popper, and R. R. Fay (Eds.), Hearing by Whales and Dolphins (1st ed., pp. 43–108). New York, NY: Springer-Verlag.

Ketten, D. R. and D. Mountain. (2009). Final Report: Modeling Minke Whale Hearing. Submitted to E&P Sound and Marine Life Programme.

Kooyman, G. L. and E. E. Sinnett. (1982). Pulmonary shunts in harbor seals and sea lions during simulated dives to depth. Physiological Zoology 55 (1): 105–111.

Kooyman, G. L., J. P. Schroeder, D. M. Denison, D. D. Hammond, J. J. Wright, and W. P. Bergman. (1972). Blood nitrogen tensions of seals during simulated deep dives. American Journal of Physiology 223 (5): 1016–1020.

Kooyman, G. L., D. H. Kerem, W. B. Campbell, and J. J. Wright. (1973). Pulmonary gas exchange in freely diving Weddell seals, *Leptonychotes weddelli*. Respiration Physiology 17 283–290.

Koski, W. R., and Johnson, S. R. (1987). Responses of bowhead whales to an offshore drilling operation in the Alaskan Beaufort Sea, Autumn 1986: Behavioral studies and aerial photogrammetry. Responses Of Bowhead Whales to An Offshore Drilling Operation in The Alaskan Beaufort Sea, Autumn 1986.

Kryter, K.D., Ward, W.D., Miller, J.D., and Eldredge, D.H. (1966). “Hazardous exposure to intermittent and steady-state noise,” Journal of the Acoustical Society of America 39, 451-464.

Kujawa, S. G. (2010). After the Noise Stops: Cochlear Nerve Degeneration Following Temporary Noise-Induced Hearing Loss. Symposium.

Kujawa, S. G. and M. C. Liberman. (2006). Acceleration of age-related hearing loss by early noise exposure: evidence of a misspent youth. Journal of Neuroscience 26 (7): 2115-2123. DOI:10.1523/JNEUROSCI.4985-05.2006

Kujawa, S. G. and M. C. Liberman. (2009). Adding insult to injury: Cochlear nerve degeneration after "temporary" noise-induced hearing loss. The Journal of Neuroscience 29 (45): 14077–14085. DOI:10.1523/JNEUROSCI.2845-09.2009

Kuningas, S., P. H. Kvadsheim, F. P. A. Lam, and P. J. O. Miller. (2013). Killer whale presence in relation to naval sonar activity and prey abundance in northern Norway. ICES Journal of Marine Science, 70(7), 1287–1293.

Kvadsheim, P. H., E. M. Sevaldsen, L. P. Folkow, and A. S. Blix. (2010). Behavioural and physiological responses of hooded seals (*Cytophora cristata*) to 1 to 7 kHz sonar signals. Aquatic Mammals, 36(3), 239–247.

Kvadsheim, P. H., S. DeRuiter, L. D. Sivle, J. Goldbogen, R. Roland-Hansen, P. J. O. Miller, F. A. Lam, J. Calambokidis, A. Friedlaender, F. Visser, P. L. Tyack, L. Kleivane, and B. Southall. (2017). Avoidance responses of minke whales to 1-4 kHz naval sonar. Marine Pollution Bulletin 121 (1–2): 60–68. DOI:10.1016/j.marpolbul.2017.05.037

Kvadsheim, P.H., Lam, F.P.A., Isojunno, S., Wensveen, P.J., Ijssemuide, S.P.V., López, L.M.M., van Riet, M.W., Henderson, E.E., Siemensma, M.L., Bort, J. and Burslem, A. (2020). Studying the effect of source proximity in sperm whales and continuous sonar in pilot whales using operational sonars-the 3S-2019-OPS cruise report.

Lam, F. P., Kvadsheim, P. H., Isojunno, S., Wensveen, P. J., van IJsselmuide, S., Siemensma, M., Dekeling, R., and Miller, P. J. O. (2018a). Behavioral response study on the effects of continuous sonar on sperm whales in Norwegian waters: The S3-2016-CAS cruise report.

Lam, F. P., Kvadsheim, P. H., Isojunno, S., IJsselmuide, S. V., Wensveen, P. J., Hansen, R. R., Sivle, L. D., Kleivane, L., López, L. M. M., Benti, B., Dekeling, R., and Miller, P. J. O. (2018b). Behavioral response study on the effects of continuous sonar and the effects of source proximity on sperm Whales in Norwegian waters: The S3-2017-CAS cruise report.

Lam, F. P., Kvadsheim, P., Miller, P. (2021) 3S3: Behavioral responses of sperm whales to naval sonar. Final Brief on Project 29 to Living Marine Resources. Program Review Meeting November 16-18, 2021.

Lammers M. O., Au W. W. L., Herzing D. L. (2003) The broadband social acoustic signaling behavior of spinner and spotted dolphins. J Acoust Soc Am 114:1629–1639.

Lavender, A. L., S. M. Bartol, and I. K. Bartol. (2014). Ontogenetic investigation of underwater hearing capabilities in loggerhead sea turtles (*Caretta caretta*) using a dual testing approach. The Journal of Experimental Biology 217 (Pt 14): 2580–2589. DOI:10.1242/jeb.096651

Lemonds, D.W., Kloepper, L.N., Nachtigall, P.E., Au, W.W.L., Vlachos, S.A., and Branstetter, B.K. (2011). “A re-evaluation of auditory filter shape in delphinid odontocetes: Evidence of constant-bandwidth filters,” Journal of the Acoustical Society of America 130, 3107-3114.

Lenhardt, M. L. (1994). Seismic and very low frequency sound induced behaviors in captive loggerhead marine turtles (Caretta caretta). Presented at the Proceedings of the Fourteenth Annual Symposium on Sea Turtle Biology and Conservation. Hilton Head, SC.

Lester, L. A. (2012). Direct and Indirect Effects of Recreational Boats on Diamondback Terrapins (*Malaclemys terrapin*). (Unpublished doctoral dissertation). Drexel University, Philadelphia, PA. Retrieved from http://hdl.handle.net/1860/3982.

Liebschner, A., Hanke, W., Miersch, L., Dehnhardt, G., and Sauerland, M. (2005). “Sensitivity of a tucuxi (*Sotalia fluviatilis guianensis*) to airborne sound,” Journal of the Acoustical Society of America 117, 436–441.

Ljungblad, D. K., Scroggins, P. D., and Gilmartin, W. G. (1982). “Auditory thresholds of a captive Eastern Pacific bottle-nosed dolphin, *Tursiops* spp.,” Journal of the Acoustical Society of America 72, 1726-1729.

Ljungblad, D. K., Würsig, B., Swartz, S. L., and Keene, J. M. (1988). Observations on the behavioral responses of bowhead whales (*Balaena mysticetus*) to active geophysical vessels in the Alaskan Beaufort Sea. Arctic, 183-194.

Lucke, K., Siebert, U., Lepper, P. A., and Blanchet, M. A. (2009). “Temporary shift in masked hearing thresholds in a harbor porpoise (*Phocoena phocoena*) after exposure to seismic airgun stimuli,” Journal of the Acoustical Society of America 125, 4060–4070.

Lucke, K., Lepper, P.A., Blanchet, M.A., and Siebert, U. (2011). The use of an air bubble curtain to reduce the received sound levels for harbor porpoises (*Phocoena phocoena*). The Journal of the Acoustical Society of America, 130(5), 3406-3412.

Lusseau, D. (2006). The short-term behavioral reactions of bottlenose dolphins to interactions with boats in Doubtful Sound, New Zealand. Marine Mammal Science, 22(4), 802–818.

Lutcavage, M. E., P. G. Bushnell, and D. R. Jones. (1992). Oxygen stores and aerobic metabolism in the leatherback sea turtle. Canadian Journal of Zoology 70 (2): 348–351.

Madsen, P. T., Møhl, B., Nielsen, B. K., and Wahlberg, M. (2002). Male sperm whale behavior during exposures to distant seismic survey pulses. Aquatic mammals, 28(3), 231-240.

Madsen, P. T., Johnson, M., Miller, P. J. O., Aguilar Soto, N., Lynch, J., and Tyack, P. (2006). Quantitative measures of air-gun pulses recorded on sperm whales (*Physeter macrocephalus*) using acoustic tags during controlled exposure experiments. The Journal of the Acoustical Society of America, 120(4), 2366-2379.

Malme, C. I., Miles, P. R., Clark, C. W., Tyack, P., and Bird, J. E. (1984). Investigations of the potential effects of underwater noise from petroleum-industry activities on migrating gray-whale behavior. Phase 2: January 1984 migration (No. PB-86-218377/XAB; BBN-5586). Bolt, Beranek and Newman, Inc., Cambridge, MA (USA).

Malme, C. I., Miles, P. R., Tyack, P., Clark, C. W., and Bird, J. E. (1985). Investigation of the potential effects of underwater noise from petroleum-industry activities on feeding humpback whale behavior. Final report (No. PB-86-218385/XAB; BBN-5851). Bolt, Beranek and Newman, Inc., Cambridge, MA (USA).

Malme, C. I., Wursig, B., Bird, J. E., and Tyack, P. (1988). Observations of feeding gray whale responses to controlled industrial noise exposure. Port and ocean engineering under arctic conditions.

Mann, D., Bauer, G., Reep, R., Gaspard, J., Dziuk, K., and Read, L. (2009). “Auditory and tactile detection by the West Indian manatee,” (Fish and Wildlife Research Institute, St. Petersburg, Florida).

Martin, K. J., S. C. Alessi, J. C. Gaspard, A. D. Tucker, G. B. Bauer, and D. A. Mann. (2012). Underwater hearing in the loggerhead turtle (*Caretta caretta*): A comparison of behavioral and auditory evoked potential audiograms. The Journal of Experimental Biology 215 (17): 3001–3009. DOI:10.1242/jeb.066324

Martin, S. B., Lucke, K., and Barclay, D. R. (2020). Techniques for distinguishing between impulsive and non-impulsive sound in the context of regulating sound exposure for marine mammals. The Journal of the Acoustical Society of America, 147(4), 2159-2176.

Maslen, K. R. (1981). Towards a better understanding of temporary threshold shift of hearing. Applied Acoustics 14 281-318.

McCarthy, E., D. Moretti, L. Thomas, N. DiMarzio, R. Morrissey, S. Jarvis, J. Ward, A. Izzi, and A. Dilley. (2011). Changes in spatial and temporal distribution and vocal behavior of Blainville's beaked whales (*Mesoplodon densirostris*) during multiship exercises with mid-frequency sonar. Marine Mammal Science, 27(3), E206–E226.

McCauley, R. D., J. Fewtrell, A. J. Duncan, C. Jenner, M. N. Jenner, J. D. Penrose, R. I. T. Prince, A. Adhitya, J. Murdoch, and K. McCabe. (2000a). Marine seismic surveys—A study of environmental implications. Australian Petroleum Production Exploration Association Journal, 692–708.

McCauley, R. D., J. Fewtrell, A. J. Duncan, C. Jenner, M.-N. Jenner, J. D. Penrose, R. I. T. Prince, A. Adhitya, J. Murdoch, and K. A. McCabe. (2000b). Marine Seismic Surveys: Analysis and Propagation of Air-gun Signals; and Effects of Air-gun Exposure on Humpback Whales, Sea Turtles, Fishes and Squid. Bentley, Australia: Centre for Marine Science and Technology.

McDonald, B. I. and P. J. Ponganis. (2012). Lung collapse in the diving sea lion: Hold the nitrogen and save the oxygen. Biology Letters 8 1047–1049. DOI:doi: 10.1098/rsbl.2012.0743

McDonald, M. A., J. A. Hildebrand, S. M. Wiggins, D. W. Johnston, and J. J. Polovina. (2009). An acoustic survey of beaked whales at Cross Seamount near Hawaii. The Journal of the Acoustical Society of America, 125(2), 624–627.

Miksis-Olds, J. L., P. L. Donaghay, J. H. Miller, P. L. Tyack, and J. E. Reynolds, III. (2007). Simulated vessel approaches elicit differential responses from manatees. Marine Mammal Science, 23(3), 629–649.

Miller, G. W., Moulton, V. D., Davis, R. A., Holst, M., Millman, P., MacGillivray, A., and Hannay, D. (2005). Monitoring seismic effects on marine mammals—southeastern Beaufort Sea, 2001-2002. Offshore oil and gas environmental effects monitoring/Approaches and technologies. Battelle Press, Columbus, OH, 511-542.

Miller, J. D., C. S. Watson, and W. P. Covell. (1963). Deafening effects of noise on the cat. Acta Oto-Laryngologica Supplement 176 1–88.

Miller, P. J. O., N. Biassoni, A. Samuels, and P. L. Tyack. (2000). Whale songs lengthen in response to sonar. Nature, 405(6789), 903.

Miller, P. J., Johnson, M. P., Madsen, P. T., Biassoni, N., Quero, M., and Tyack, P. L. (2009). Using at-sea experiments to study the effects of airguns on the foraging behavior of sperm whales in the Gulf of Mexico. Deep Sea Research Part I: Oceanographic Research Papers, 56(7), 1168-1181.

Miller, P., R. Antunes, A. C. Alves, P. Wensveen, P. Kvadsheim, L. Kleivane, N. Nordlund, F.-P. Lam, S. van IJsselmuide, F. Visser, and P. Tyack. (2011). The 3S experiments: studying the behavioral effects of naval sonar on killer whales (*Orcinus orca*), sperm whales (*Physeter macrocephalus*), and long-finned pilot whales (*Globicephala melas*) in Norwegian waters (Scottish Oceans Inst. Tech. Rept., SOI-2011-001).

Miller, P. J. O., P. H. Kvadsheim, F.-P. A. Lam, P. J. Wensveen, R. Antunes, A. C. Alves, F. Visser, L. Kleivane, P. L. Tyack, and L. D. Sivle. (2012). The severity of behavioral changes observed during experimental exposures of killer (*Orcinus orca*), long-finned pilot (*Globicephala melas*), and sperm (*Physeter macrocephalus*) whales to naval sonar. Aquatic Mammals, 38(4), 362–401.

Miller, P. J., R. N. Antunes, P. J. Wensveen, F. I. Samarra, A. C. Alves, P. L. Tyack, P. H. Kvadsheim, L. Kleivane, F. P. Lam, M. A. Ainslie, and L. Thomas. (2014). Dose-response relationships for the onset of avoidance of sonar by free-ranging killer whales. The Journal of Acoustical Society of America, 135(2), 975–993.

Miller, P. J., P. H. Kvadsheim, F. P. Lam, P. L. Tyack, C. Cure, S. L. DeRuiter, L. Kleivane, L. D. Sivle, I. S. P. van, F. Visser, P. J. Wensveen, A. M. von Benda-Beckmann, L. M. Martin Lopez, T. Narazaki, and S. K. Hooker. (2015). First indications that northern bottlenose whales are sensitive to behavioral disturbance from anthropogenic noise. Royal Society Open Science, 2(6), 140484.

Møhl, B. (1968). “Auditory sensitivity of the common seal in air and water,” Journal of Auditory Research 8, 27-38.

Mooney, T.A., Nachtigall, P.E., and Vlachos, S. (2009a). “Sonar-induced temporary hearing loss in dolphins,” Biol. Letters 5, 565-567.

Mooney, T. A., P. E. Nachtigall, M. Breese, S. Vlachos, and W. W. L. Au. (2009b). Predicting temporary threshold shifts in a bottlenose dolphin (*Tursiops truncatus*): The effects of noise level and duration. Journal of the Acoustical Society of America 125 (3): 1816-1826.

Moore, P.W.B. and Schusterman, R.J. (1987). “Audiometric assessment of northern fur seals, *Callorhinus ursinus*,” Mar. Mammal Sci. 3, 31-53.

Moretti, D., L. Thomas, T. Marques, J. Harwood, A. Dilley, B. Neales, J. Shaffer, E. McCarthy, L. New, S. Jarvis, and R. Morrissey. (2014). A risk function for behavioral disruption of Blainville's beaked whales (*Mesoplodon densirostris*) from mid-frequency active sonar. PLoS ONE, 9(1), e85064.

Moulton, V. D., Richardson, W. J., Williams, M. T., and Blackwell, S. B. (2003). Ringed seal densities and noise near an icebound artificial island with construction and drilling. Acoustics Research Letters Online, 4(4), 112-117.

Mulsow, J. and C. Reichmuth. (2010). Psychophysical and electrophysiological aerial audiograms of a Steller sea lion (*Eumetopias jubatus*). The Journal of the Acoustical Society of America 127 (4): 2692–2701.

Mulsow, J.L., Finneran, J.J., and Houser, D.S. (2011). “California sea lion (*Zalophus californianus*) aerial hearing sensitivity measured using auditory steady-state response and psychophysical methods,” Journal of the Acoustical Society of America 129, 2298-2306.

Mulsow, J., Houser, D.S., and Finneran, J.J. (2012). “Underwater psychophysical audiogram of a young male California sea lion (*Zalophus californianus*),” Journal of the Acoustical Society of America 131, 4182-4187.

Mulsow, J., C. E. Schlundt, L. Brandt, and J. J. Finneran. (2015). Equal latency contours for bottlenose dolphins (*Tursiops truncatus*) and California sea lions (*Zalophus californianus*). The Journal of the Acoustical Society of America 138 (5): 2678-2691.

Mulsow, J., C. E. Schlundt, M. G. Strahan, and J. J. Finneran. (2023). Bottlenose dolphin temporary threshold shift following exposure to 10-ms impulses centered at 8 kHz. The Journal of the Acoustical Society of America 154 (2): 1287-1298.

Nachtigall, P.E., Au, W.W.L., Pawloski, J., and Moore, P.W.B. (1995). “Risso’s dolphin (*Grampus griseus*) hearing thresholds in Kaneohe Bay, Hawaii,” in Sensory Systems of Aquatic Mammals, edited by R.A. Kastelein, J.A. Thomas, and P.E. Nachtigall (DeSpil, Woerden, The Netherlands), pp. 49-53.

Nachtigall, P.E., Pawloski, J., and Au, W.W.L. (2003). “Temporary threshold shifts and recovery following noise exposure in the Atlantic bottlenosed dolphin (*Tursiops truncatus*),” Journal of the Acoustical Society of America 113, 3425-3429.

Nachtigall, P.E., Supin, A.Y., Pawloski, J., and Au, W.W.L. (2004). “Temporary threshold shifts after noise exposure in the bottlenose dolphin (*Tursiops truncatus*) measured using evoked auditory potentials,” Mar. Mammal Sci. 20, 673-687.

National Marine Fisheries Service (2016). Technical Guidance for Assessing the Effects of Anthropogenic Sound on Marine Mammal Hearing—Underwater Acoustic Thresholds for Onset of Permanent and Threshold Shifts. Silver Springs, MD: National Oceanic and Atmospheric Administration.

National Marine Fisheries Service. (2018). Revision to: Technical Guidance for Assessing the Effects of Anthropogenic Sound on Marine Mammal Hearing (Version 2.0) —Underwater Acoustic Thresholds for Onset of Permanent and Temporary Threshold Shifts. Silver Springs, MD: National Oceanic and Atmospheric Administration.

National Research Council (NRC) (2003). Ocean Noise and Marine Mammals (National Academies Press, Washington, DC). 219 pp.

Nedwell, J., Langworthy, J., and Howell, D. (2003). Assessment of sub-sea acoustic noise and vibration from offshore wind turbines and its impact on marine wildlife; initial measurements of underwater noise during construction of offshore windfarms, and comparison with background noise. Subacoustech Report ref: 544R0423, published by COWRIE.

Nelms, S. E., W. E. D. Piniak, C. R. Weir, and B. J. Godley. (2016). Seismic surveys and marine turtles: An underestimated global threat? Biological Conservation 193 49–65.

Nowacek, D. P., M. P. Johnson, and P. L. Tyack. (2004). North Atlantic right whales (*Eubalaena glacialis*) ignore ships but respond to alerting stimuli. Proceedings of the Royal Society of London, 271(B), 227–231.

Nowacek, D. P., L. H. Thorne, D. W. Johnston, and P. L. Tyack. (2007). Responses of cetaceans to anthropogenic noise. Mammal Review, 37(2), 81–115.

Nowacek, S. M., R. S. Wells, E. C. G. Owen, T. R. Speakman, R. O. Flamm, and D. P. Nowacek. (2004). Florida manatees, *Trichechus manatus latirostris*, respond to approaching vessels. Biological Conservation, 119, 517–523.

O'Hara, J. and J. R. Wilcox. (1990). Avoidance responses of loggerhead turtles, *Caretta caretta*, to low frequency sound. Copeia 1990 (2): 564–567.

O'Keeffe, D. J. and G. A. Young. (1984). Handbook on the Environmental Effects of Underwater Explosions. Silver Spring, MD: U.S. Navy, Naval Surface Weapons Center (Code R14).

Owen, M.A. and Bowles, A.E. (2011). “In-air auditory psychophysics and the management of a threatened carnivore, the polar bear (Ursus maritimus),” Int. J. Comp. Psychol. 24, 244-254.

Parks, S. E., D. R. Ketten, J. T. O’Malley, and J. Arruda. (2007a). Anatomical predictions of hearing in the North Atlantic right whale. The Anatomical Record 290 734–744.

Parks, S. E., C. W. Clark, and P. L. Tyack. (2007b). Short- and long-term changes in right whale calling behavior: The potential effects of noise on acoustic communication. The Journal of Acoustical Society of America, 122(6), 3725–3731.

Parks, S. E., M. Johnson, D. Nowacek, and P. L. Tyack. (2011). Individual right whales call louder in increased environmental noise. Biology Letters, 7, 33–35.

Piniak, W. E. D., S. A. Eckert, C. A. Harms, and E. M. Stringer. (2012). Underwater Hearing Sensitivity of the Leatherback Sea Turtle (*Dermochelys coriacea*): Assessing the Potential Effect of Anthropogenic Noise (OCS Study BOEM 2012-01156). Herndon, VA: U.S. Department of the Interior, Bureau of Ocean Energy Management.

Piniak, W. E. D., D. A. Mann, C. A. Harms, T. T. Jones, and S. A. Eckert. (2016). Hearing in the juvenile green sea turtle (*Chelonia mydas*): A comparison of underwater and aerial hearing using auditory evoked potentials. PLoS ONE 11 (10): e0159711.

Pirotta, E., N. D. Merchant, P. M. Thompson, T. R. Barton, and D. Lusseau. (2015). Quantifying the effect of boat disturbance on bottlenose dolphin foraging activity. Biological Conservation, 181, 82–89.

Piscitelli, M. A., W. A. McLellan, A. S. Rommel, J. E. Blum, S. G. Barco, and D. A. Pabst. (2010). Lung size and thoracic morphology in shallow and deep-diving cetaceans. Journal of Morphology 271 654–673. DOI:DOI: 10.1002/jmor.10823

Popov, V.V., Supin, A.Y., Wang, D., Wang, K., Dong, L., and Wang, S. (2011a). “Noise-induced temporary threshold shift and recovery in Yangtze finless porpoises *Neophocaena phocaenoides asiaeorientalis*,” Journal of the Acoustical Society of America 130, 574-584.

Popov, V.V., Klishin, V.O., Nechaev, D.I., Pletenko, M.G., Rozhnov, V.V., Supin, A.Y., Sysueva, E.V., and Tarakanov, M.B. (2011b). “Influence of acoustic noises on the white whale hearing thresholds,” Doklady Biological Sciences 440, 332-334.

Popov, V.V., Supin, A.Y., Rozhnov, V.V., Nechaev, D.I., Sysuyeva, E.V., Klishin, V.O., Pletenko, M.G., and Tarakanov, M.B. (2013). “Hearing threshold shifts and recovery after noise exposure in beluga whales *Delphinapterus leucas*,” Journal of Experimental Biology 216, 1587-1596.

Popov, V.V., Supin, A.Y., Rozhnov, V.V., Nechaev, D.I., and Sysueva, E.V. (2014). “The limits of applicability of the sound exposure level (SEL) metric to temporal threshold shifts (TTS) in beluga whales, *Delphinapterus leucas*,” Journal of Experimental Biology 217, 1804-1810.

Popov, V. V., D. I. Nechaev, E. V. Sysueva, V. V. Rozhnov, and A. Y. Supin. (2015). Spectrum pattern resolution after noise exposure in a beluga whale, *Delphinapterus leucas*: Evoked potential study. The Journal of the Acoustical Society of America 138 (1): 377–388. DOI:10.1121/1.4923157

Popper, A. N., A. D. Hawkins, R. R. Fay, D. A. Mann, S. M. Bartol, T. J. Carlson, S. Coombs, W. T. Ellison, R. L. Gentry, M. B. Halvorsen, S. Løkkeborg, P. H. Rogers, B. L. Southall, D. G. Zeddies, and W. N. Tavolga. (2014). ASA S3/SC1.4 TR-2014 Sound Exposure Guidelines for Fishes and Sea Turtles: A Technical Report prepared by ANSI-Accredited Standards Committee S3/SC1 and registered with ANSI. New York, NY and London, United Kingdom: Acoustical Society of America Press and Springer Briefs in Oceanography.

Reeves, R. R., B. S. Stewart, P. J. Clapham, and J. A. Powell. (2002). National Audubon Society Guide to Marine Mammals of the World. New York, NY: Alfred A. Knopf.

Reichmuth, C. (2013). Equal loudness contours and possible weighting functions for pinnipeds. The Journal of the Acoustical Society of America 134 (5): 4210 (A).

Reichmuth, C. and Southall, B.L. (2012). “Underwater hearing in California sea lions (*Zalophus californianus*): Expansion and interpretation of existing data,” Mar. Mammal Sci. 28, 358-363.

Reichmuth, C., Holt, M.M., Mulsow, J., Sills, J.M., and Southall, B.L. (2013). “Comparative assessment of amphibious hearing in pinnipeds,” Journal of Comparative Physiology A 199, 491-507.

Reichmuth, C., A. Ghoul, A. Rouse, J. Sills, and B. Southall. (2016). Low-frequency temporary threshold shift not observed in spotted or ringed seals exposed to single air gun impulses. The Journal of the Acoustical Society of America 140 (4): 2646-2658.

Reichmuth, C., Sills, J.M., and Ghoul, A. (2017). “Psychophysical audiogram of a California sea lion listening for airborne tonal sounds in an acoustic chamber,” Proceedings of Meetings on Acoustics 30, 010001.

Reichmuth, C., J. M. Sills, J. Mulsow, and A. Ghoul. (2019). Long-term evidence of noise-induced permanent threshold shift in a harbor seal (Phoca vitulina). The Journal of the Acoustical Society of America 146 (4): 2552-2561. DOI:10.1121/1.5129379

Reichmuth, C.J., Sills, J., Mulsow, J., Holt, M., and Southall, B.L. (2024). “Temporary threshold shifts from mid-frequency airborne noise exposures in seals,” J. Acoust. Soc. Am. (in prep).

Richardson, W. J., Fraker, M. A., Würsig, B., and Wells, R. S. (1985). Behaviour of bowhead whales *Balaena mysticetus* summering in the Beaufort Sea: Reactions to industrial activities. Biological Conservation, 32(3), 195-230.

Richardson, W. J., Würsig, B., and Greene Jr, C. R. (1986). Reactions of bowhead whales, *Balaena mysticetus*, to seismic exploration in the Canadian Beaufort Sea. The Journal of the Acoustical Society of America, 79(4), 1117-1128.

Richardson, W. J., C. R. Greene, Jr., C. I. Malme, and D. H. Thomson. (1995). Marine Mammals and Noise. San Diego, CA: Academic Press.

Richardson, W. J., Miller, G. W., and Greene Jr, C. R. (1999). Displacement of migrating bowhead whales by sounds from seismic surveys in shallow waters of the Beaufort Sea. The Journal of the Acoustical Society of America, 106(4), 2281-2281.

Richmond, D. R., J. T. Yelverton, and E. R. Fletcher. (1973). Far-Field Underwater-Blast Injuries Produced by Small Charges. Washington, DC: Lovelace Foundation for Medical Education and Research, Defense Nuclear Agency.

Ridgway, S. H. (1972). Homeostasis in the Aquatic Environment. In S. H. Ridgway (Ed.), Mammals of the Sea: Biology and Medicine (pp. 590–747). Springfield, IL: Charles C. Thomas.

Ridgway, S. H. and R. Howard. (1979). Dolphin lung collapse and intramuscular circulation during free diving: Evidence from nitrogen washout. Science 206 1182–1183.

Ridgway, S. H., D. A. Carder, R. R. Smith, T. Kamolnick, C. E. Schlundt, and W. R. Elsberry. (1997). Behavioral Responses and Temporary Shift in Masked Hearing Threshold of Bottlenose Dolphins, *Tursiops truncatus*, to 1-second Tones of 141 to 201 dB re 1 µPa. San Diego, CA: U.S. Department of Navy, Naval Command, Control and Ocean Surveillance Center, Research, Development, Test, and Evaluation Division.

Ridgway, S.H., Carder, D.A., Kamolnick, T., Smith, R.R., Schlundt, C.E., and Elsberry, W.R. (2001). “Hearing and whistling in the deep sea: depth influences whistle spectra but does not attenuate hearing by white whales (*Delphinapterus leucas*) (Odontoceti, Cetacea),” Journal of Experimental Biology 204, 3829-3841.

Ruscher, B., Sills, J.M., Richter, B.P., and Reichmuth, C. (2021). “In-air hearing in Hawaiian monk seals: implications for understanding the auditory biology of Monachinae seals,” J Comp Physiol A 207, 561-573.

Russell, D. J., Hastie, G. D., Thompson, D., Janik, V. M., Hammond, P. S., Scott-Hayward, L. A., and McConnell, B. J. (2016). Avoidance of wind farms by harbour seals is limited to pile driving activities. Journal of Applied Ecology, 53(6), 1642-1652.

Ryan, A. F., S. G. Kujawa, T. Hammill, C. Le Prell, and J. Kil. (2016). Temporary and Permanent Noise-induced Threshold Shifts: A Review of Basic and Clinical Observations. Otology and Neurotology 37 (8): e271-275. DOI:10.1097/MAO.0000000000001071

Salas, A. K., A. M. Capuano, C. A. Harms, W. E. D. Piniak, and T. A. Mooney. (2023a). Temporary noise-induced underwater hearing loss in an aquatic turtle (*Trachemys scripta elegans*). The Journal of the Acoustical Society of America 154 (2): 1003-1017. DOI:10.1121/10.0020588

Salas, A. K., A. M. Capuano, C. Harms, W. E. D. Piniak, and T. A. Mooney. (2023b). Calculating Underwater Auditory Thresholds in the Freshwater Turtle *Trachemys scripta elegans*. In A. N.

Popper, J. A. Sisneros, A. D. Hawkins, and F. Thomsen (Eds.), The Effects of Noise on Aquatic Life. Springer, Cham.

Salas, A. K., A. M. Capuano, C. A. Harms, W. E. D. Piniak, and T. A. Mooney. (2024). Frequency-dependent temporary threshold shifts in the Eastern Painted Turtle (*Chrysemys picta picta*). The Journal of the Acoustical Society of America 155(5): DOI: 10.1121/10.0026021.

Sarnocińska, J., Teilmann, J., Balle, J. D., van Beest, F. M., Delefosse, M., and Tougaard, J. (2020). Harbor porpoise (*Phocoena phocoena*) reaction to a 3D seismic airgun survey in the North Sea. Frontiers in Marine Science, 824.

Sauerland, M. and Dehnhardt, G. (1998). "Underwater audiogram of a tucuxi (*Sotalia fluviatilis guianensis*)," Journal of the Acoustical Society of America 103, 1199-1204.

Schaffeld, T., Ruser, A., Woelfing, B., Baltzer, J., Kristensen, J.H., Larsson, J., Schnitzler, J.G., and Siebert, U. (2019). "The use of seal scarers as a protective mitigation measure can induce hearing impairment in harbour porpoises," J. Acoust. Soc. Am. 146, 4288-4298.

Scheidat, M., Tougaard, J., Brasseur, S., Carstensen, J., van Polanen Petel, T., Teilmann, J., and Reijnders, P. (2011). Harbour porpoises (*Phocoena phocoena*) and wind farms: a case study in the Dutch North Sea. Environmental Research Letters, 6(2), 025102.

Schlundt, C. E., Finneran, J. J., Carder, D. A., and Ridgway, S. H. (2000). Temporary shift in masked hearing thresholds of bottlenose dolphins, *Tursiops truncatus*, and white whales, Delphinapterus leucas, after exposure to intense tones. The Journal of the Acoustical Society of America, 107(6), 3496-3508.

Schlundt, C.E., Dear, R.L., Green, L., Houser, D.S., and Finneran, J.J. (2007). "Simultaneously measured behavioral and electrophysiological hearing thresholds in a bottlenose dolphin (*Tursiops truncatus*)," Journal of the Acoustical Society of America 122, 615-622.

Schorr, G. S., E. A. Falcone, D. J. Moretti, and R. D. Andrews. (2014). First long-term behavioral records from Cuvier's beaked whales (*Ziphius cavirostris*) reveal record-breaking dives. PLoS ONE, 9(3), e92633.

Schusterman, R.J. (1974). "Auditory sensitivity of a California sea lion to airborne sound," Journal of the Acoustical Society of America 756, 1248-1251.

Schusterman, R.J., Balliet, R.F., and Nixon, J. (1972). "Underwater audiogram of the California sea lion by the conditioned vocalization technique," J. Exp. Anal. Behav. 17, 339-350.

Schusterman, R. J., B. L. Southall, D. Kastak, and C. R. Kastak. (2001). Pinniped Vocal Communication: Form and Function. Paper presented at the Proceedings of the International Congress on Acoustics, Rome, Italy.

Sills, J.M., Southall, B.L., and Reichmuth, C. (2014). "Amphibious hearing in spotted seals (*Phoca largha*): underwater audiograms, aerial audiograms and critical ratio measurements," Journal of Experimental Biology 217, 726-734.

Sills, J.M., Southall, B.L., and Reichmuth, C. (2015). "Amphibious hearing in ringed seals (*Pusa hispida*): underwater audiograms, aerial audiograms and critical ratio measurements," J. Exp. Biol. 218, 2250-2259.

Sills, J.M., Reichmuth, C., Southall, B.L., Whiting, A., and Goodwin, J. (2020a). "Auditory biology of bearded seals (*Erignathus barbatus*)," Polar Biol. 43, 1681-1691.

Sills, J. M., B. Ruscher, R. Nichols, B. L. Southall, and C. Reichmuth. (2020b). Evaluating temporary threshold shift onset levels for impulsive noise in seals. The Journal of the Acoustical Society of America 148 (5): 2973-2986. DOI:10.1121/10.0002649

Sills, J.M., Parnell, K., Ruscher-Hill, B., Lew, C., Kendall, T.L., and Reichmuth, C. (2021). "Underwater hearing and communication in the endangered Hawaiian monk seal, *Neomonachus schauinslandi*," Endangered Species Research 44, 61-78.

Simonis, A. E., Forney, K. A., Rankin, S., Ryan, J., Zhang, Y., DeVogelaere, A., and Baumann-Pickering, S. (2020). Seal bomb noise as a potential threat to Monterey Bay Harbor Porpoise. Frontiers in Marine Science, 7, 142.

Sivle, L. D., P. H. Kvadsheim, A. Fahlman, F. P. Lam, P. L. Tyack, and P. J. Miller. (2012). Changes in dive behavior during naval sonar exposure in killer whales, long-finned pilot whales, and sperm whales. Frontiers in Physiolology, 3, 400.

Sivle, L. D., P. H. Kvadsheim, C. Curé, S. Isojunno, P. J. Wensveen, F. A. Lam, F. Visser, L. Kleivane, P. L. Tyack, C. M. Harris, and P. J. O. Miller. (2015). Severity of expert-identified behavioural responses of humpback whale, minke whale, and northern bottlenose whale to naval sonar. Aquatic Mammals, 41(4), 469–502.

Skeate, E. R., Perrow, M. R., and Gilroy, J. J. (2012). Likely effects of construction of Scroby Sands offshore wind farm on a mixed population of harbour *Phoca vitulina* and grey *Halichoerus grypus* seals. Marine pollution bulletin, 64(4), 872-881.

Southall, B. L., A. E. Bowles, W. T. Ellison, J. J. Finneran, R. L. Gentry, C. R. Greene, Jr., D. Kastak, D. R. Ketten, J. H. Miller, P. E. Nachtigall, W. J. Richardson, J. A. Thomas, and P. L. Tyack. (2007). Marine mammal noise exposure criteria: Initial scientific recommendations. Aquatic Mammals, 33(4), 411–521.

Southall, B., J. Calambokidis, P. Tyack, D. Moretti, J. Hildebrand, C. Kyburg, R. Carson, A. Friedlaender, E. Falcone, G. Schorr, A. Douglas, S. DeRuiter, J. Goldbogen, and J. Barlow. (2011). Biological and Behavioral Response Studies of Marine Mammals in Southern California, 2010 ("SOCAL-10"). Pearl Harbor, HI: U.S. Navy Pacific Fleet.

Southall, B., J. Calambokidis, P. Tyack, D. Moretti, A. Friedlaender, S. DeRuiter, J. Goldbogen, E. Falcone, G. Schorr, A. Douglas, A. Stimpert, J. Hildebrand, C. Kyburg, R. Carlson, T. Yack, and J. Barlow. (2012). Biological and Behavioral Response Studies of Marine Mammals in Southern California, 2011 ("SOCAL-11") Final Project Report (SOCAL-11 Project Report).

Southall, B., J. Calambokidis, J. Barlow, D. Moretti, A. Friedlaender, A. Stimpert, A. Douglas, K. Southall, S. Arranz, S. DeRuiter, E. Hazen, J. Goldbogen, E. Falcone, and G. Schorr. (2013). Biological and Behavioral Response Studies of Marine Mammals in Southern California, 2012 ("SOCAL-12").

Southall, B., J. Calambokidis, J. Barlow, D. Moretti, A. Friedlaender, A. Stimpert, A. Douglas, K. Southall, P. Arranz, S. DeRuiter, J. Goldbogen, E. Falcone, and G. Schorr. (2014). Biological and Behavioral Response Studies of Marine Mammals in Southern California, 2013 ("SOCAL-13"). Pearl Harbor, HI: U.S. Navy Pacific Fleet.

Southall, B. L., D. P. Nowacek, P. J. O. Miller, and P. L. Tyack. (2016). Experimental field studies to measure behavioral responses of cetaceans to sonar. Endangered Species Research 31 293–315. DOI:10.3354/esr00764

Southall, B. L., J. J. Finneran, C. Reichmuth, P. E. Nachtigall, D. R. Ketten, A. E. Bowles, W. T. Ellison, D. P. Nowacek, and P. L. Tyack. (2019a). Marine mammal noise exposure criteria: Updated scientific recommendations for residual hearing effects. Aquatic Mammals 45 (2): 125–232. DOI:10.1578/am.45.2.2019.125

Southall, B.L., DeRuiter, S.L., Friedlaender, A., Stimpert, A.K., Goldbogen, J.A., Hazen, E., Casey, C., Fregosi, S., Cade, D.E., Allen, A.N. and Harris, C.M. (2019b). Behavioral responses of individual blue whales (*Balaenoptera musculus*) to mid-frequency military sonar. Journal of Experimental Biology, 222(5), p.jeb190637.

Southall, B. L., Nowacek, D. P., Bowles, A. E., Senigaglia, V., Bejder, L., and Tyack, P. L. (2021). Marine mammal noise exposure criteria: assessing the severity of marine mammal behavioral responses to human noise. Aquatic Mammals, 47(5), 421-464.

Southall, B. L., Allen, A. N., Calambokidis J., Casey, C., DeRuiter, S. L., Fregosi, S., Friedlander, A. S., Goldbogen, J. A., Harris, C. M., Hazen, E. L., Popov, V., and A. K. Stimpert. (2023). Behavioural responses of fin whales to military mid-frequency active sonar. Royal Society Open Science, 10:231775.

Stimpert, A. K., S. L. DeRuiter, B. L. Southall, D. J. Moretti, E. A. Falcone, J. A. Goldbogen, A. Friedlaender, G. S. Schorr, and J. Calambokidis. (2014). Acoustic and foraging behavior of a Baird's beaked whale, *Berardius bairdii*, exposed to simulated sonar. Scientific Reports, 4, 7031.

Szymanski, M.D., Bain, D.E., Kiehl, K., Pennington, S., Wong, S., and Henry, K.R. (1999). “Killer whale (*Orcinus orca*) hearing: Auditory brainstem response and behavioral audiograms,” Journal of the Acoustical Society of America 106, 1134-1141.

Teilmann, J., Carstensen, J., Dietz, R., and Edrén, S. M. C. (2004). Effect on seals at Rødsand seal sanctuary from the construction of Nysted offshore wind farm based on aerial surveys. Commissioned by ENERGI E2 A/S, National Environmental Research Institute, Roskilde, Denmark.

Teilmann, J., Tougaard, J., L. A. Miller, T. Kirketerp, K. Hansen, and S. Brando. (2006). Reactions of captive harbor porpoises (*Phocoena phocoena*) to pinger-like sounds. Marine Mammal Science, 22(2), 240–260.

Terhune, J.M. (1988). “Detection thresholds of a harbour seal to repeated underwater high-frequency, short-duration sinusoidal pulses,” Can. J. Zool. 66, 1578-1582.

Terhune, J.M. and Ronald, K. (1972). “The harp seal, *Pagophilus groenlandicus* (Erxleben, 1777) III. The underwtater audiogram,” Can. J. Zool. 50, 565-569.

Terhune, J.M. and Ronald, K. (1975). “Masked hearing thresholds of ringed seals,” Journal of the Acoustical Society of America 58, 515-516.

Thomas, J., Chun, N., Au, W., and Pugh, K. (1988). “Underwater audiogram of a false killer whale (*Pseudorca crassidens*),” Journal of the Acoustical Society of America 84, 936-940.

Thomas, J., Moore, P., Withrow, R., and Stoermer, M. (1990). “Underwater audiogram of a Hawaiian monk seal (*Monachus schauinslandi*),” Journal of the Acoustical Society of America 87, 417-420.

Thompson, P. M., Lusseau, D., Barton, T., Simmons, D., Rusin, J., and Bailey, H. (2010). Assessing the responses of coastal cetaceans to the construction of offshore wind turbines. Marine pollution bulletin, 60(8), 1200-1208.

Tougaard, J., Carstensen, J., Damsgaard Henriksen, O., and Teilmann, J. (2003). Short-term effects of the construction of wind turbines on harbour porpoises at Horns Reef. Technical report to TechWise A/S. HME/362-02662, Hedeselskabet, Roskilde.

Tougaard, J., Carstensen, J., Teilmann, J., Bech, N. I., Skov, H., and Henriksen, O. D. (2005). Effects of the Nysted Offshore wind farm on harbour porpoises. Annual Status Report for the T-POD Monitoring Program.

Tougaard, J., Carstensen, J., Teilmann, J., Skov, H., and Rasmussen, P. (2009). Pile driving zone of responsiveness extends beyond 20 km for harbor porpoises (*Phocoena phocoena* (L.)). Journal of the Acoustical Society of America, 126(1), 11.

Tougaard, J., Beedholm, K., and Madsen, P. T. (2022). Thresholds for noise induced hearing loss in harbor porpoises and phocid seals. The Journal of the Acoustic Society of America 151 (6): 4252-4263.

Tremel, D.P., Thomas, J.A., Ramierez, K.T., Dye, G.S., Bachman, W.A., Orban, A.N., and Grimm, K.K. (1998). “Underwater hearing sensitivity of a Pacific white-sided dolphin, *Lagenorhynchus obliquidens*,” Aquat. Mammal. 24, 63-69.

Tubelli, A.A., Zosuls, A., Ketten, D.R., Yamato, M., and Mountain, D.C. (2012). “A prediction of the minke whale (*Balaenoptera acutorostrata*) middle-ear transfer function,” Journal of the Acoustical Society of America 132, 3263-3272.

Tyack, P. L. (1999). Responses of Baleen whales to controlled exposures of low-frequency sounds from a naval sonar. The Journal of the Acoustical Society of America, 106(4), 2280-2280.

Tyack, P. L. and Clark, C. W. (2000). Communication and acoustic behavior of dolphins and whales. In W. W. L. Au, A. N. Popper, and R. R. Fay (Eds.), Hearing by Whales and Dolphins (pp. 156–224). New York, NY: Springer.

Tyack, P. L., Zimmer, W. M. X., Moretti, D., Southall, B. L., Claridge, D. E., Durban, J. W., Clark, C. W., D'Amico, A., DiMarzio, N., Jarvis, S., McCarthy, E., Morrissey, R., Ward, J., and Boyd, I. L. (2011). Beaked whales respond to simulated and actual Navy sonar. PLoS ONE, 6(3), 15.

U.S. Department of the Navy. (2001). Final Environmental Impact Statement (EIS)/Overseas Environmental Impact Statement (OEIS) for the Shock Trial of the USS WINSTON S. CHURCHILL (DDG 81). Washington, DC: U.S. Department of the Navy.

U.S. Department of the Navy. (2003). Report on the Results of the Inquiry into Allegations of Marine Mammal Impacts Surrounding the Use of Active Sonar by USS SHOUP (DDG 86) in the Haro Strait on or about 5 May 2003.

U.S. Department of the Navy. (2008). Final Environmental Impact Statement (EIS)/Overseas Environmental Impact Statement (OEIS) for the Shock Trial of the MESA VERDE (LPD 19). Washington, DC: U.S. Department of the Navy.

U.S. Department of the Navy. (2017). Criteria and Thresholds for U.S. Navy Acoustic and Explosive Effects Analysis (Phase III). San Diego, CA: Space and Naval Warfare Systems Command, Pacific.

U.S. Department of the Navy. (2024). Criteria and Thresholds for U.S. Navy Acoustic and Explosive Effects Analysis (Phase IV). San Diego, CA: Naval Information Warfare Center, Pacific.

Urick, R. J. (1983). Principles of Underwater Sound, Principles of Underwater Sound for Engineers (3rd ed.). Los Altos Hills, CA: Peninsula Publishing.

Virtanen, P., Gommers, R., Oliphant, T.E., Haberland, M., Reddy, T., Cournapeau, D., Burovski, E., Peterson, P., Weckesser, W., and Bright, J. (2020). “SciPy 1.0: Fundamental algorithms for scientific computing in Python,” Nature methods 17, 261-272.

von Benda-Beckmann, A. M., Wensveen, P. J., Prior, M., Ainslie, M. A., Hansen, R. R., Isojunno, S., and Miller, P. J. O. (2019). Predicting acoustic dose associated with marine mammal behavioural responses to sound as detected with fixed acoustic recorders and satellite tags. The Journal of the Acoustical Society of America, 145(3), 1401-1416.

Wang, D., Wang, K., Xiao, Y., and Sheng, G. (1992). “Auditory sensitivity of a Chinese River dolphin, *Lipotes vexillifer*,” in Marine Mammal Sensory Systems, edited by J.A. Thomas, R.A. Kastelein, and A.Y. Supin (Plenum Press, New York), pp. 213-221.

Ward, W. D. (1960). Recovery from high values of temporary threshold shift. The Journal of the Acoustical Society of America 32 (4): 497–500.

Ward, W. D. (1997). Effects of high-intensity sound. In M. J. Crocker (Ed.), Encyclopedia of Acoustics (pp. 1497-1507). New York, NY: Wiley.

Ward, W.D., Glorig, A., and Sklar, D.L. (1958). “Dependence of temporary threshold shift at 4 kc on intensity and time,” Journal of the Acoustical Society of America 30(10): 944-954.

Ward, W.D., Glorig, A., and Sklar, D.L. (1959). “Temporary Threshold Shift from Octave-Band Noise: Applications to Damage-Risk Criteria,” Journal of the Acoustical Society of America 31(4): 522-528.

Wartzok, D. and Ketten, D. R. (1999). Marine Mammal Sensory Systems. In J. E. Reynolds, III & S. A. Rommel (Eds.), Biology of Marine Mammals (pp. 117–175). Washington, DC: Smithsonian Institution Press.

Wartzok, D., Popper, A. N., Gordon, J., and Merrill, J. (2003). Factors affecting the responses of marine mammals to acoustic disturbance. Marine Technology Society Journal, 37(4), 6-15.

Watwood, S. L., J. D. Iafrate, E. A. Reyier, and W. E. Redfoot. (2016). Behavioral Response of Reef Fish and Green Sea Turtles to Mid-Frequency Sonar. In A. N. Popper & A. Hawkins (Eds.), The Effects of Noise on Aquatic Life II (pp. 1213–1221). New York, NY: Springer.

Wensveen, P. J., L. A. Huijser, L. Hoek, and R. A. Kastelein. (2014). Equal latency contours and auditory weighting functions for the harbour porpoise (*Phocoena phocoena*). The Journal of Experimental Biology 217 (Pt 3): 359–369. DOI:10.1242/jeb.091983

Wensveen, P. J., Isojunno, S., Hansen, R. R., von Benda-Beckmann, A. M., Kleivane, L., van IJsselmuide, S., and Miller, P. J. (2019). Northern bottlenose whales in a pristine environment respond strongly to close and distant navy sonar signals. Proceedings of the Royal Society B, 286(1899), 20182592.

White, M.J., Norris, J., Ljungblad, D.K., Baron, K., and di Sciara, G.N. (1978). “Auditory thresholds of two beluga whales (*Delphinapterus leucas*),” (Hubbs Sea World Research Institute, San Diego).

Williams, R., Ashe, E., Sandilands, D., & Lusseau, D. (2011). Stimulus-dependent response to disturbance affecting the activity of killer whales. The Scientific Committee of the International Whaling Commission, Document: SC/63/WW5, 1-27.

Williams, R., Erbe, C., Ashe, E., Beerman, A., and Smith, J. (2014). Severity of killer whale behavioral responses to ship noise: a dose-response study. Marine Pollution Bulletin, 79(1-2), 254–260.

Wolski, L.F., Anderson, R.C., Bowles, A.E., and Yochem, P.K. (2003). “Measuring hearing in the harbor seal (*Phoca vitulina*): Comparison of behavioral and auditory brainstem response techniques,” Journal of the Acoustical Society of America 113, 629-637.

Yelverton, J. T. and Richmond, D. R. (1981). Underwater explosion damage risk criteria for fish, birds, and mammals [Type]. Presented at the 102nd Meeting of the Acoustical Society of America Miami Beach, FL.

Yelverton, J. T., Richmond, D. R., Fletcher, E. R., and Jones, R. K. (1973). Safe Distances From Underwater Explosions for Mammals and Birds. Albuquerque, NM: Lovelace Foundation for Medical Education and Research.

Yuen, M.M.L., Nachtigall, P.E., Breese, M., and Supin, A.Y. (2005). “Behavioral and auditory evoked potential audiograms of a false killer whale (*Pseudorca crassidens*),” Journal of the Acoustical Society of America 118, 2688–2695.

Zeyl, J. N. (2016). Hearing evolution across the air-water interface: lessons from comparative audiometry in turtles and salamanders. (Doctoral Dissertation). Auburn University, Auburn, Alabama.

APPENDIX A. AUDIOGRAM DATA

Table A-1. Audiogram datasets used for creating composite audiograms.

Group	Species	Study	Animals	Notes
HF	*Delphinapterus leucas*	Awbrey 1988	Adult female	
			Kojak	1 kHz excluded (already in White 1978)
			Subadult male	
		Finneran 2005a	Beethoven	
		Johnson 1989	Female	
		Ridgway 2001	MUK	
			NOC	
		White 1978	Edwina	
			Kojak	
	Lagenorhynchus obliquidens	Tremel 1998	Female	
	Orcinus orca	Branstetter 2017	C	
			D	
			E	
			F	
			G	
			H	
		Szymanski 1999	Vigga	
			Yaka	
	Pseudorca crassidens	Thomas 1988	I'a nui hahai	
	Sotalia fluviatilis	Sauerland 1998	Paco	
	Stenella coeruleoalba	Kastelein 2003	ScSH001	
	Tursiops truncatus	Finneran 2010a	TYH	
		Johnson 1967	Salty	
		Lemonds 2011	Itsi Bitsy	
VHF	*Inia geoffrensis*	Jacobs 1972	N/a	
	Phocoena phocoena	Kastelein 2002a	PpSH047	
		Kastelein 2010	Jerry (02)	
		Kastelein 2015a	ID No. 04	

Table A-1. Audiogram datasets used for creating composite audiograms. (Continued)

Group	Species	Study	Animals	Notes
VHF	*Phocoena phocoena*	Kastelein 2017a	Pp05	
			Pp06	
SI	*Trichechus manatus latirostris*	Gaspard 2012	Buffet	
			Hugh	
		Gerstein 1999	Dundee	Excluded data below 400 Hz (tactile perception)
			Stormy	Excluded data below 400 Hz (tactile perception)
OCA	*Callorhinus ursinus*	Babushina 1991	N/a	
		Moore 1987	Lori	
			Tobe	
	Enhydra lutris nereis	Ghoul 2014	Charlie	
	Eumetopias jubatus	Mulsow 2010	Astro	
	Ursus maritimus	Owen 2011	SD Zoo	Mean of 2 animals
			SeaWorld SD	Mean of 3 animals
	Zalophus californianus	Moore 1987	Rocky	
		Mulsow 2011	JFN	
		Reichmuth 2013	Rio	
		Reichmuth 2017	Ronan	
OCW	*Callorhinus ursinus*	Babushina 1991	N/a	
		Moore 1987	Lori	
			Tobe	
	Enhydra lutris nereis	Ghoul 2014	Charlie	
	Eumetopias jubatus	Kastelein 2005	EjZH021	
			EjZH022	
	Odobenus rosmarus divergens	Kastelein 2002	OrZH 003 (Igor)	
	Zalophus californianus	Cunningham 2016	Ronan	50 kHz and above only
		Kastak 1998	Rocky	
		Kastelein 2023a	F01	
			M02	

Table A-1. Audiogram datasets used for creating composite audiograms. (Continued)

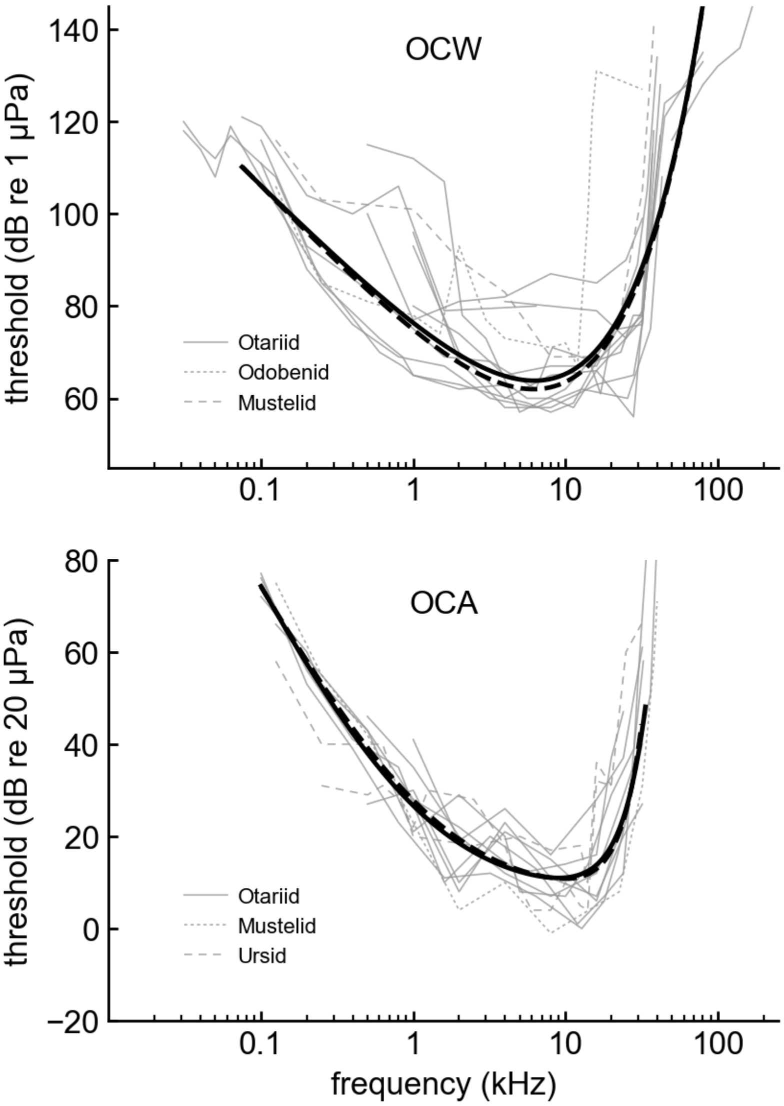
Group	Species	Study	Animals	Notes
OCW	*Zalophus californianus*	Mulsow 2012	JFN	
		Reichmuth 2012	Rio	
		Reichmuth 2013	Ronan	
PCA	*Phoca largha*	Sills 2014	Amak	
			Tunu	
	Phoca vitulina	Reichmuth 2013	Sprouts	
	Pusa hispida	Sills 2015	Nayak	
PCW	*Erignathus barbatus*	Sills 2020a	Noatak	
			Siku	
	Mirounga angustirostris	Kastak 1999	Burnyce	
	Neomonachus schauinslandi	Sills 2021	Kekoa	
	Pagophilus groenlandicus	Terhune 1972	Female	
	Phoca largha	Cunningham 2016	Tunu	
		Sills 2014	Amak	
			Tunu	
	Phoca vitulina	Cunningham 2016	Sprouts	80 kHz and above only
		Kastelein 2009b	SM.Pv. 01	
			SM.Pv. 02	
		Reichmuth 2013	Sprouts	
		Terhune 1988	N/a	
	Pusa hispida	Sills 2015	Nayak	

Table A-2. Audiogram datasets available but not used for composite audiogram creation.

Group	Species	Study	Animals	Notes
HF	*Delphinapterus leucas*	Finneran 2005a	Turner	High-frequency hearing loss
	Grampus griseus	Nachtigall 1995	Hana	Suspected broadband hearing loss
	Orcinus orca	Branstetter 2017	A	Broadband hearing loss
			B	Low-frequency hearing loss
		Hall 1972	Subadult male	High-frequency hearing loss
	Pseudorca crassidens	Yuen 2005	Kina	High-frequency hearing loss
	Sotalia fluviatilis	Liebschner 2005	Paco	Tested in air
	Tursiops truncatus	Brill 2001	CAS	Thresholds masked by ambient noise
			HEP	High-frequency hearing loss
		Cook 2006	Ranier	Broadband hearing loss
		Finneran 2007	BLU	High-frequency hearing loss
		Schlundt 2007	WEN	Tested in air
	Tursiops truncatus gilli	Ljungblad 1982	12-y female	Aberrant audiogram
VHF	*Lipotes vexillifer*	Wang 1992	Qi Wi	High-frequency hearing loss
	Phocoena phocoena	Andersen 1970	N/a	Elevated thresholds near upper limit
SI	*Trichechus manatus latirostris*	Mann 2009	Buffet	Represented in Gaspard 2012
			Hugh	Represented in Gaspard 2012
OCA	*Odobenus rosmarus divergens*	Kastelein 1996	OrZH003 (Igor)	Thresholds appear masked
			OrZH003 (Igor)	Thresholds appear masked
	Zalophus californianus	Holt 2012	Rio	Represented in Reichmuth 2013
		Kastak 1998	Rocky	Elevated thresholds
		Schusterman 1974	Sam	Abberant audiogram shape for species
OCW		Cunningham 2016	Ronan	Data below 50 kHz excluded
		Kastak 1998	Rio	Data from Reichmuth 2012 used instead
		Kastak 2002	Newman	Elevated thresholds
		Schusterman 1972	Sam	Elevated thresholds

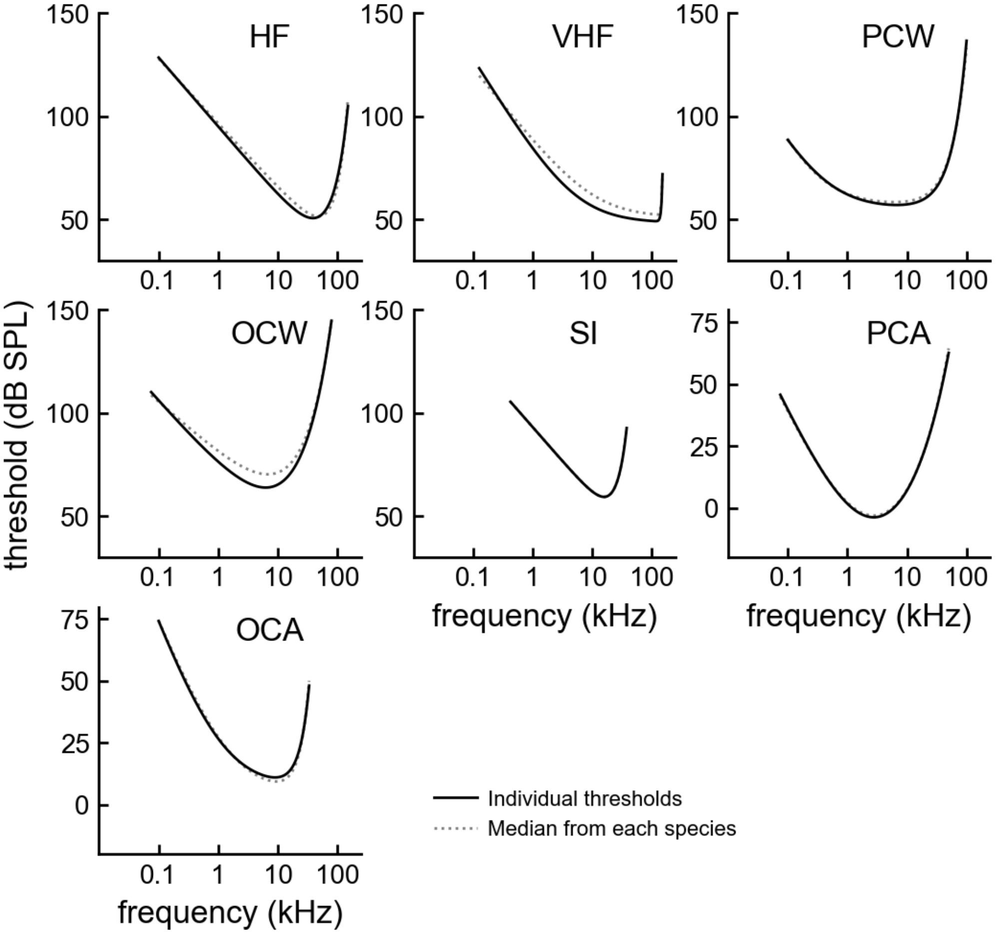
Table A-2. Audiogram datasets available but not used for composite audiogram creation. (Continued)

Group	Species	Study	Animals	Notes
PCA	*Mirounga angustirostris*	Kastak 1998	Burnyce	Monachid thresholds very high re: other phocids
		Kastak 1999	Burnyce	Monachid thresholds very high re: other phocids
	Mirounga angustirostris	Reichmuth 2013	Burnyce	Monachid thresholds very high re: other phocids
	Neomonachus schauinslandi	Ruscher 2021	KE18	Monachid in-air thresholds very high re: other phocids
	Phoca vitulina	Kastak 1998	Sprouts	Represented in Reichmuth 2013
		Møhl 1968	3–4 y Male	Uncontrolled environment, elevated thresholds
		Wolski 2003	SWCPV9614B	Elevated thresholds near 2 kHz
			SWCPV9614B	Elevated thresholds
	Pusa caspica	Babushina 1997	Adult female	Elevated thresholds
	Pusa hispida	Sills 2015	Natchek	High-frequency hearing loss in underwater measurements
PCW	*Mirounga angustirostris*	Kastak 1998	Burnyce	Represented in Kastak 1999
	Monachus schauinslandi	Thomas 1990	Maka	Elevated thresholds below 10 kHz
	Phoca vitulina	Cunningham 2016	Sprouts	Data below 80 kHz represented in Reichmuth 2013
		Kastak 1998	Sprouts	Represented in Reichmuth 2013
		Kastelein 2009a	SM.Pv. 01	Pure tone thresholds in Kastelein 2009b
			SM.Pv. 02	Pure tone thresholds in Kastelein 2009b
		Møhl 1968	3 – 4 y Male	Elevated thresholds
	Pusa caspica	Babushina 1997	Adult female	Elevated thresholds
	Pusa hispida	Sills 2015	Natchek	High-frequency hearing loss
		Terhune 1975	Female	Elevated thresholds
			Male	Elevated thresholds



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.

Figure A-1. Comparison of Otariid, Mustelid, Odobenid, and Ursid psychophysical hearing thresholds measured underwater (top) and in-air (bottom).



The thick, solid line is the composite audiogram based on the median of the individual threshold data.

The dotted line is the composite audiogram based on the median of the thresholds for each species; i.e., the median threshold was first computed for each species, then the median of these data was computed.

Figure A-2. Comparison of composite thresholds for groups with audiogram data.

APPENDIX B. ESTIMATING MYSTICETE AUDIOGRAMS

B.1. BACKGROUND

Psychophysical and/or electrophysiological auditory threshold data exist for at least one species within each hearing group, except for the mysticetes, for which auditory thresholds have not been directly measured. For this reason, composite audiograms for mysticetes must be estimated.

Mathematical models based on anatomical data have been used to predict hearing curves for several mysticete species (e.g., Cranford & Krysl, 2015; Ketten & Mountain, 2009). However, these predictions are not directly used to derive the Phase 4 composite mysticete audiograms because: (1) There are no peer-reviewed publications that provide a complete description of the process by which anatomical frequency-place maps were integrated with middle-ear transfer functions to predict the audiograms (e.g., Ketten & Mountain, 2009). (2) The fin whale model (Cranford & Krysl, 2015) does not include the sensory receptors of the inner ear, therefore the upper cutoff of hearing and audiogram shape above the region of best sensitivity cannot be predicted. Furthermore, the predicted audiogram does not possess the typical shape one would expect for an individual with normal hearing based on measurements from other mammals.

Vocalization data also cannot solely be used to estimate auditory thresholds and audible range, since there are many examples of mammals that vocalize with energy below the frequency range where they have best hearing sensitivity, and well below their upper frequency limit (UFL) of hearing (including cattle, dogs, and humans, see Heffner & Heffner, 1992). 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. Similarly, behavioral observations of animals reacting to sound playbacks can be used to evaluate the proposed audiogram, but cannot be used to directly derive the function, since it is impossible to know if the animals detected the sound but simply did not react (i.e., the data do not permit absolute sensitivity to be determined).

The first direct measurements of the hearing abilities of mysticetes was recently obtained by Houser et al. (2024), who measured supra-threshold auditory brainstem responses (ABRs) in two minke whales. Testing with broadband tone-burst stimuli in one of the whales revealed that the UFL was between 45 and 90 kHz. Since only supra-threshold data were obtained, these data cannot be used to directly create an audiogram; however, they do provide guidance on the audible frequency range and specifically the UFL of hearing.

Given the limited nature of the available data, Phase 4 mysticete audiograms were estimated not from any one source but by synthesizing information from a variety of sources, including: minke whale supra-threshold ABRs (Houser et al., 2024); cochlear frequency-place maps created from anatomical measurements of basilar membrane dimensions (e.g., Ketten, 1994; Parks et al., 2007a); scaling relationships between mammalian inter-aural time differences and UFL (see Ketten, 2000); finite element models of head-related and middle-ear transfer functions (Cranford & Krysl, 2015; Tubelli et al., 2012); model-based predictions of relative hearing sensitivity for the humpback whale (Houser et al., 2001); measurements of the source levels and frequency content of mysticete vocalizations (see review by Tyack & Clark, 2000); and observations of mysticete reactions to sound playbacks (e.g., Boisseau et al., 2021; Kvadsheim et al., 2017). These data were then supplemented with extrapolations from the other marine mammal species groups where necessary.

B.2. MYSTICETE HEARING GROUPS

In Navy Phase 3 analyses, all mysticetes were placed in a single hearing group, designated “low-frequency (LF) cetaceans”. However, recent ABR data (Houser et al., 2024) showing a relatively high (45–90 kHz) UFL for minke whales now supports separating mysticetes into two hearing groups for Phase 4, designated as “very-low frequency (VLF) cetaceans” and “low-frequency (LF) cetaceans.” Splitting the mysticetes in such a way, and the categorization of the various species into the two groups (Table B-1), follows the recommendations of Southall et al. (2019a)

Table B-1. Mysticete hearing groups.

Group	Name	Members
VLF	Very low frequency cetaceans	Balaenidae (right and bowhead whales): *Eubalaena* spp., *Balaena* Balaenopteridae: *Balaenoptera physalus* (fin whale), *B. musculus* (blue whale)
LF	Low frequency cetaceans	Balaenopteridae: *Balaenoptera acutorostrata* (common minke whale), *B. bonaerensis* (Antarctic minke whale), *B. borealis* (sei whale), *B. edeni* (Bryde's whale), *B. omurai* (Omura's whale), *B. ricei* (Rice's whale), *Megaptera novaeangliae* (humpback whale) Eschrichtiidae (gray whale): *Eschrichtius* Neobalenidae (pygmy right whale): *Caperea*

For Navy Phase 4, the VLF composite audiogram matches the original mysticete (LF) composite audiogram from Phase 3. The Phase 4 LF composite audiogram was created by shifting the LF curve upwards in frequency to account for new minke whale ABR data (Houser et al., 2024). The frequency shift was based on the ratio of the UFL estimated for minke whales (64 kHz, the geometric mean of 45 and 90 kHz), and the original UFL estimated for mysticetes (30 kHz), or 64/30=2.13.

B.3. AUDIOGRAM FUNCTIONAL FORM AND REQUIRED PARAMETERS

Composite audiograms are defined by the equation

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

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

$$T_0 + L(f) + H(f) \qquad (\mathrm{B}-2)$$

where

$$L(f) = A\log_{10}\left(1 + \frac{F_1}{f}\right) \qquad (\mathrm{B}-3)$$

and

$$H(f) = \left(\frac{f}{F_2}\right)^B \qquad (\mathrm{B}-4)$$

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. (B-3) approaches

$$L(f) = A\log_{10}\left(\frac{F_1}{f}\right) \qquad (\mathrm{B}-5)$$

which can also be written as

$$L(f) = A\log_{10}\ F_1 - A\log_{10}\ f \qquad (\mathrm{B}-6)$$

Equation (B-6) has the form of $y(x) = b - Ax$, where $x = \log_{10}\ f$; i.e., Eq. (B-6) describes a linear function of the logarithm of frequency. This means that, as frequency decreases, Eq. (B-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 $f \ll F_2$, Eq. (B-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 slope.

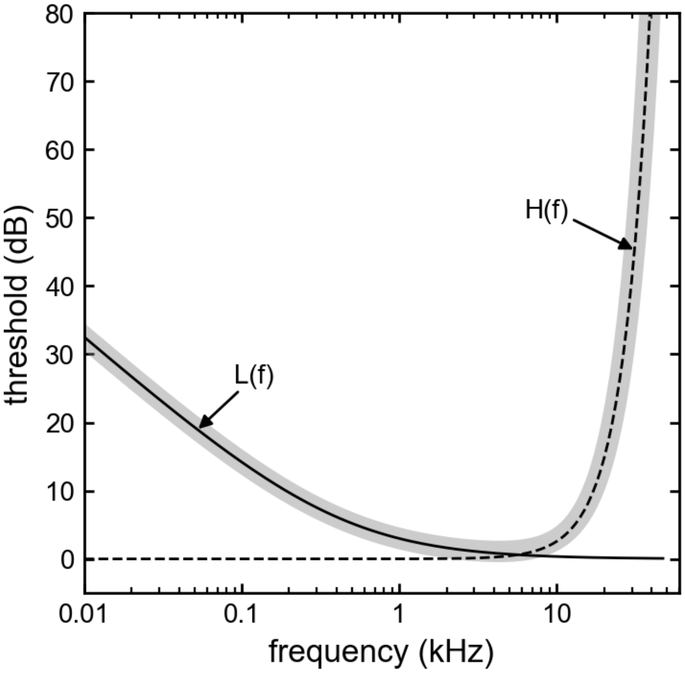


Figure B-1. Relationship between estimated threshold, T(f), (thick, gray line), low-frequency term, L(f), (solid line), and high-frequency term, H(f), (dashed line).

B.4. ESTIMATING AUDIOGRAM PARAMETERS

To derive composite mysticete audiograms using Eq. (B-1), the values of T_0, F_1, F_2, A, and B must be defined. The constant A is defined by assuming a value for the low-frequency slope of the audiogram, in $\mathrm{dB}/$ decade. Most mammals for which thresholds have been measured have lowfrequency slopes ~ 30 to $40\ \mathrm{dB}/$ decade. However, finite element models of middle ear function in fin whales (Cranford & Krysl, 2015) and minke whales (Tubelli et al., 2012) suggest lower slopes, of ~ 25 or $20\ \mathrm{dB}/$ decade, respectively. We therefore conservatively assume that $A = 20\ \mathrm{dB}/$ decade for both the VLF and LF groups.

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 $T'\mathrm{dB}$ 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. (B-3) can then be solved for F_1 as a function of f', T', and A :

$$F_1 = f'\left(10^{T'/A} - 1\right) \qquad (\mathrm{B} - 7)$$

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. (2007a) 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 $3-\mathrm{dB}$ of best sensitivity from ~ 1 to 1.5 kHz. Together, these model results broadly suggest best sensitivity (thresholds within $\sim 3\ \mathrm{dB}$ of the lowest threshold) from ~ 1 to 8 kHz, and thresholds within $\sim 40\ \mathrm{dB}$ of best sensitivity as low as $\sim 30\ \mathrm{Hz}$ and up to $\sim 25\mathrm{kHz}$.

Based on this information, we assume VLF cetacean thresholds are within 3 dB of the lowest threshold over a frequency range of 1 to 8 kHz, therefore $T' = 3\ \mathrm{dB}$ and $f' = 1\mathrm{kHz}$, resulting in $F_1 = 0.412\ \mathrm{kHz}$ for the VLF group [Eq. (B-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). For the LF group, f' is shifted upwards by a factor of $64/30$, or 2.13 (see below), resulting in $F_1 = 0.880\ \mathrm{kHz}$ for the LF group.

To define the high-frequency portion of the audiogram, the values of B and F_2 must be estimated. To estimate B for both VLF and LF cetaceans, the median of the B values from the composite audiograms for the other in-water species groups is used (HF=1.66, VHF=24.5, SI=2.5, OCW=0.786, and PCW=1.79). This results in B= 1.79 for the VLF and LF cetaceans.

Once B is defined, F_2 is adjusted to achieve a threshold value at the UFL that is 40 dB higher than the lowest threshold. For VLF cetaceans, the UFL is estimated to be 30 kHz. This results in $F_2 =$ 3.73 kHz for VLF cetaceans. For LF cetaceans, the UFL is estimated to be 64 kHz. This value was chosen since it is midway between 45 and 90 kHz on a logarithmic scale, which is the way frequencies are mapped within the mammalian inner ear. A UFL of 64 kHz results in $F_2 = 7.97$ kHz for LF cetaceans.

Finally, T_0 is adjusted to set the lowest threshold value from the composite audiogram to a specific SPL. For Navy Phase 4 analyses, the lowest VLF and LF cetacean thresholds are matched to the mean threshold of the in-water marine mammal species groups (HF, VHF, SI, OCW, PCW; mean = 56 dB re 1 µPa); this results in T_0 = 54.2 dB for both the VLF and LF groups.

The resulting composite audiograms are shown in Figure B-2. For comparison, predicted audiograms for the fin whale (Cranford & Krysl, 2015), and humpback whale (Houser et al., 2001) are included. The VLF cetacean composite audiogram has lowest threshold at 2.8 kHz, but the audiogram is fairly shallow in the region of best sensitivity and thresholds are within 3 dB of the lowest threshold from ~ 0.55 to 8.5 kHz. Low-frequency ($<\sim 500\ \mathrm{Hz}$) 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 70 dB above best threshold. The LF cetacean composite audiogram has lowest threshold at $\sim 6\mathrm{kHz}$ and thresholds are within 3 dB of the lowest threshold from $\sim$ 1.2 to 20 kHz. The resulting composite audiograms appear reasonable considering 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 calls occur in the range of a few tens of Hz to a few kHz, overlapping reasonably well with the predicted auditory sensitivity shown in the composite audiograms (within ~ 0 to 30 dB of predicted best sensitivity). A general pattern of some vocalizations 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), Steller sea lions (Mulsow & Reichmuth, 2010), and some terrestrial mammals, notably the Indian elephant (Heffner & Heffner, 1982, 1992).

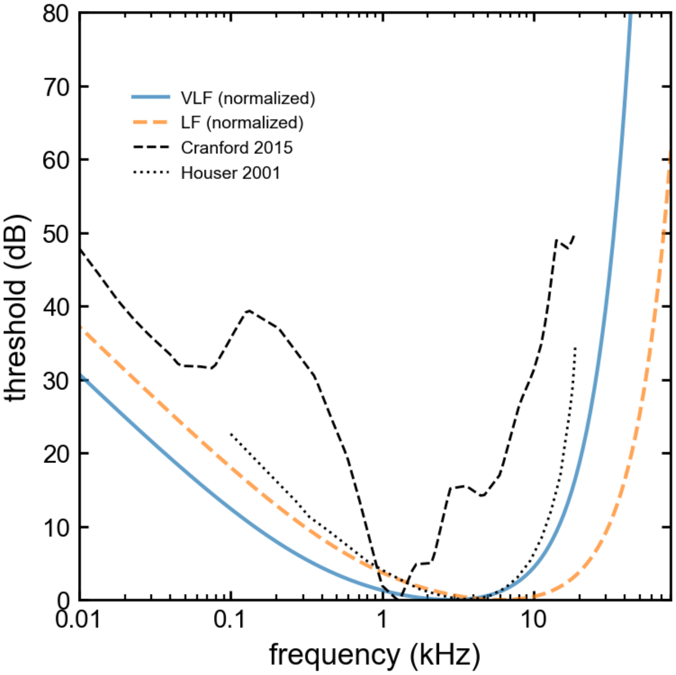
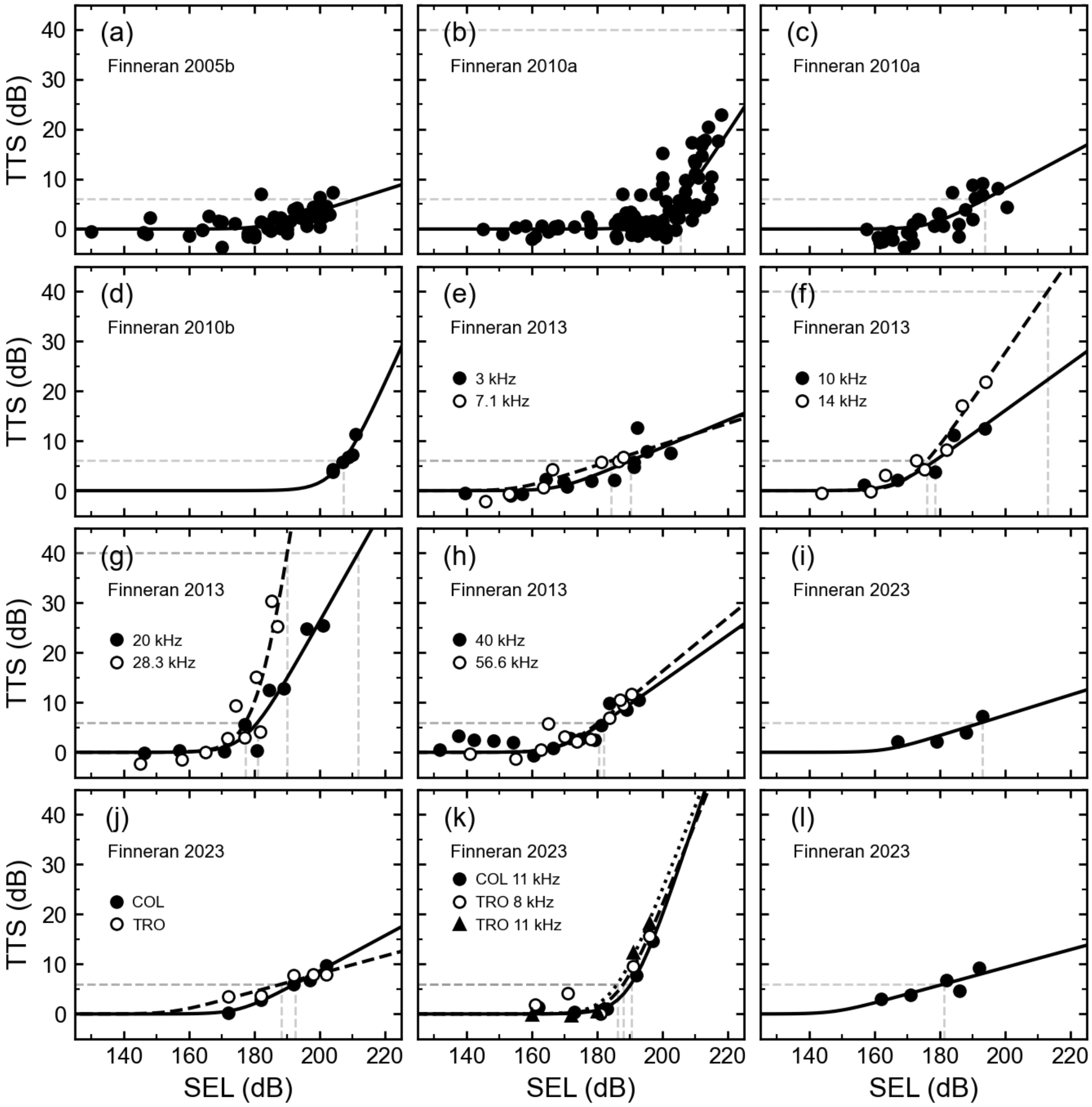


Figure B-2. Comparison of (normalized) proposed VLF and LF cetacean composite audiograms to those predicted by anatomical and finite-element models.

APPENDIX C. MARINE MAMMAL TTS GROWTH CURVES



Growth curves were obtained by fitting Eq. (6) to the TTS data as a function of SEL.

Onset TTS was defined as the SEL value from the fitted curve at $\text{TTS} = 6\ \text{dB}$ (shown with light gray dashed lines), for only those datasets that bracketed 6 dB of TTS.

Onset AINJ was defined as the SEL value from the fitted curve at a $\text{TTS} = 40\ \text{dB}$, for only those datasets with maximum $\text{TTS} > 20\ \text{dB}$.

Solid lines are fit to the filled circles, dashed lines are fit to the open circles, and the dotted line is fit to the triangles.

See Table C-1 for explanation of the datasets in each panel. SEL units are dB re $1\ \mu\text{Pa}^2\text{s}$.

Figure C-1. TTS growth data for HF cetaceans obtained using behavioral methods.

Table C-1. Summary of group HF TTS growth data and onset exposure levels.

Group	Species	Study	Subject	Exp. Freq. (kHz)	Hear. Freq. (kHz)	Min TTS (dB)	Max TTS (dB)	TTS onset (dB SEL)	TTS growth rate (dB/dB)	INJ onset (dB SEL)	INJ-TTS offset (dB)	Notes	Panel
HF	*Tursiops truncatus*	Finneran 2005b	BEN	3	4.5	0	7.4	211**	0.21	-	-	TTS onset higher than subsequent tests	(a)
		Finneran 2010a	BLU	3	4.5	0	23	206**	1	241	35	TTS onset higher than subsequent tests	(b)
			TYH	3	4.5	0	9.1	194	0.35	-	-	-	(c)
		Finneran 2010b	BLU	3	4.5	3.8	11	207**	1.5	-	-	Intermittent	(d)
		Finneran 2013	BLU	3	4.5	0	13	190	0.27	-	-	-	(e)
				7.1	10	0	6.7	184	0.21	-	-	-	(e)
				10	14	1.2	12	178	0.47	-	-	-	(f)
				14.1	20	0	22	176	0.95	213	37	-	(f)
				20	30	0	25	181	1.2	212	31	-	(g)
				28.3	40	0	30	177	4.5	190	13	-	(g)

Table C-1. Summary of group HF TTS growth data and onset exposure levels. (Continued)

Group	Species	Study	Subject	Exp. Freq. (kHz)	Hear. Freq. (kHz)	Min TTS (dB)	Max TTS (dB)	TTS onset (dB SEL)	TTS growth rate (dB/dB)	INJ onset (dB SEL)	INJ-TTS offset (dB)	Notes	Panel
HF	*Tursiops truncatus*	Finneran 2013	TYH	40	56.6	0	10	182	0.46	-	-	-	(h)
				56.6	80	0	12	181	0.54	-	-	-	(h)
		Finneran 2023	COL	0.5	0.5	2.2	7.2	193	0.2	-	-	-	(i)
				2	2	0.2	9.8	192	0.35	-	-	-	(j)
				8	11.3	0.4	15	190	2	-	-	-	(k)
			TRO	2	2	3.5	7.9	188	0.18	-	-	-	(j)
				8	8	0.1	16	188**	1.7	-	-	Lower TTS onset at 11 kHz	(k)
				8	11.3	0	18	186	1.7	-	-	-	(k)
				20	20	3	9.3	181	0.18	-	-	-	(l)

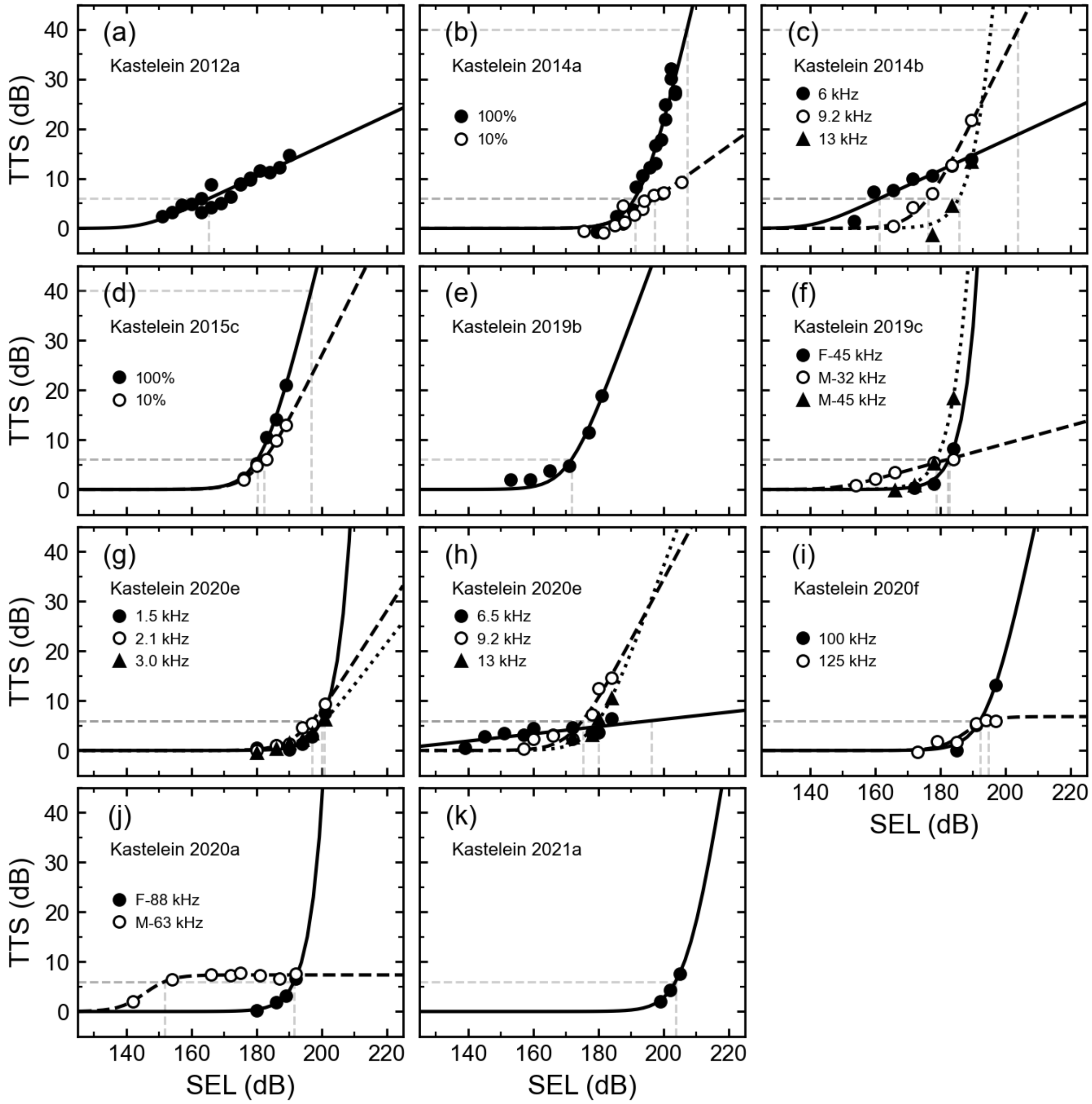
Only those data from which growth curves could be generated are included.

TTS onset values are expressed in SEL, in dB re $1\ \mu\mathrm{Pa}^2\mathrm{s}$.

Tests featured exposure to steady-state noise and behavioral threshold measurements.

"Panel" refers to corresponding sub-panel plot within Figure C-1.

** Data excluded from mean onset TTS calculation. 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) a lower TTS onset was found at a different hearing test frequency (also see Notes).



Growth curves were obtained by fitting Eq. (6) or (7) to the TTS data as a function of SEL.

Onset TTS was defined as the SEL value from the fitted curve at TTS = 6 dB, for only those datasets that bracketed 6 dB of TTS.

Onset AINJ was defined as the SEL value from the fitted curve at a TTS $= \mathbf{40}\ \mathrm{dB}$, for only those datasets with maximum TTS $> \mathbf{20}\ \mathrm{dB}$.

Solid lines are fit to the filled circles, dashed lines are fit to the open circles, and dotted lines fit to the triangles.

See Table C-2 for explanation of the datasets in each panel. SEL units are dB re $1\ \mu\mathrm{Pa}^2\mathrm{s}$.

Figure C-2. TTS growth data for VHF cetaceans obtained using behavioral methods.

Table C-2. Summary of group VHF TTS growth data and onset exposure levels.

Group	Species	Study	Subject	Exp. Freq. (kHz)	Hear. Freq. (kHz)	Min TTS (dB)	Max TTS (dB)	TTS onset (dB SEL)	TS growth rate (dB/dB)	INJ onset (dB SEL)	INJ-TTS offset (dB)	Notes	Panel
VHF	*Phocoena phocoena*	Kastelein 2012a	2	4	4	2.4	15	165	0.31	-	-	-	(a)
		Kastelein 2014a	2	1.5	1.5	0	32	191	2.8	207	16	100% duty cycle	(b)
				1.5	1.5	0	9.4	197**	0.47	-	-	10% duty cycle	(b)
		Kastelein 2014b	2	6.5	6.5	1.4	14	161	0.3	-	-	-	(c)
				6.5	9.2	0.5	22	176**	1.3	204	28	TTS onset at lower SEL at 6.5 kHz	(c)
				6.5	13	0	13	186**	11	-	-	TTS onset at lower SEL at 6.5 kHz	(c)
		Kastelein 2015c	2	6.5	9.2	2.3	21	180**	2.7	197	17	Same subject, higher TTS onset re: Kastelein 2014a	(d)
				6.5	9.2	2	13	182**	1.3	-	-	10% duty cycle	(d)
		Kastelein 2019b	M06	16	22.4	1.9	19	172*	1.8	-	-	-	(e)
		Kastelein 2019c	F05	32	44.8	0.4	8.2	183**	8.4×10^3	-	-	16-min post-exposure testing	(f)

Table C-2. Summary of group VHF TTS growth data and onset exposure levels. (Continued)

Group	Species	Study	Subject	Exp. Freq. (kHz)	Hear. Freq. (kHz)	Min TTS (dB)	Max TTS (dB)	TTS onset (dB SEL)	TTS growth rate (dB/dB)	INJ onset (dB SEL)	INJ-TTS offset (dB)	Notes	Panel
VHF	*Phocoena phocoena*	Kastelein 2019c	M06	32	32	0.8	6.1	182**	0.18	-	-	Lower TTS onset at 44.8 kHz	(f)
				32	44.8	0	18	179*	19	-	-	-	(f)
		Kastelein 2020a	F05	63	88.4	0.2	6.6	192*	1.1×10^3	-	-	-	(j)
			M06	63	63	2.1	7.8	152*	-	-	-	-	(j)
		Kastelein 2020e	F05	1.5	1.5	0.2	7.6	200**	2.5×10^3	-	-	Lower TTS onset at 2.1 kHz	(g)
				1.5	2.1	0	9.3	197	1	-	-	-	(g)
				1.5	3	0	6.2	201**	0.85	-	-	Lower TTS onset at 2.1 kHz	(g)
				6.5	6.5	0.5	6.4	196**	0.07	-	-	Lower TTS onset at 9.2 kHz	(h)
				6.5	9.2	0.3	15	175	1.2	-	-	-	(h)
				6.5	13	2.7	11	180**	1.8	-	-	Lower TTS onset at 9.2 kHz	(h)

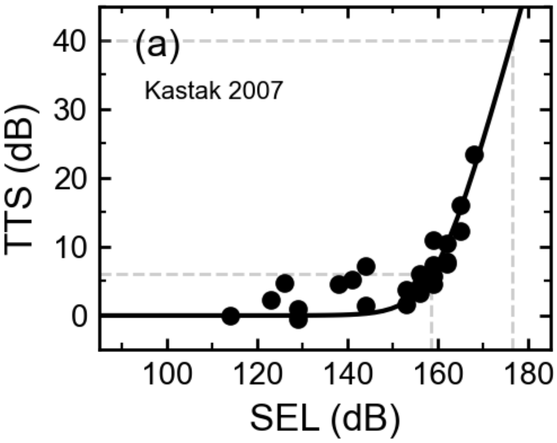
Table C-2. Summary of group VHF TTS growth data and onset exposure levels. (Continued)

Group	Species	Study	Subject	Exp. Freq. (kHz)	Hear. Freq. (kHz)	Min TTS (dB)	Max TTS (dB)	TTS onset (dB SEL)	TTS growth rate (dB/dB)	INJ onset (dB SEL)	INJ-TTS offset (dB)	Notes	Panel
VHF	*Phocoena phocoena*	Kastelein 2020f	F05	88.4	100	0.1	13	192*	3.1	-	-	-	(i)
				88.4	125	0	6.1	195**	-	-	-	Lower TTS onset at 100 kHz	(i)
		Kastelein 2021a	F05	0.5	0.5	2.1	7.6	204	4.4	-	-	-	(k)

Only those data from which growth curves could be generated are included. TTS onset values are expressed in SEL, in dB re $1\ \mu\mathrm{Pa}^2\mathrm{s}$. Tests featured continuous exposure to steadystate noise and behavioral threshold measurements. "Panel" refers to corresponding sub-panel plot within Figure C-2.

* SELs not used during exposure function fitting process.

** Data excluded from mean onset TTS calculation. 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) a lower TTS onset was found at a different hearing test frequency (also see Notes).



The growth curve was obtained by fitting Eq. (6) to the TTS data as a function of SEL.
Onset TTS was defined as the SEL value from the fitted curve at TTS $= 6$ dB.
Onset AINJ was defined as the SEL value from the fitted curve at a TTS $= 40$ dB.
See Table C-3 for explanation of the dataset. SEL units are $\mathrm{dB\ re\ 20\ \mu Pa^2 s}$.

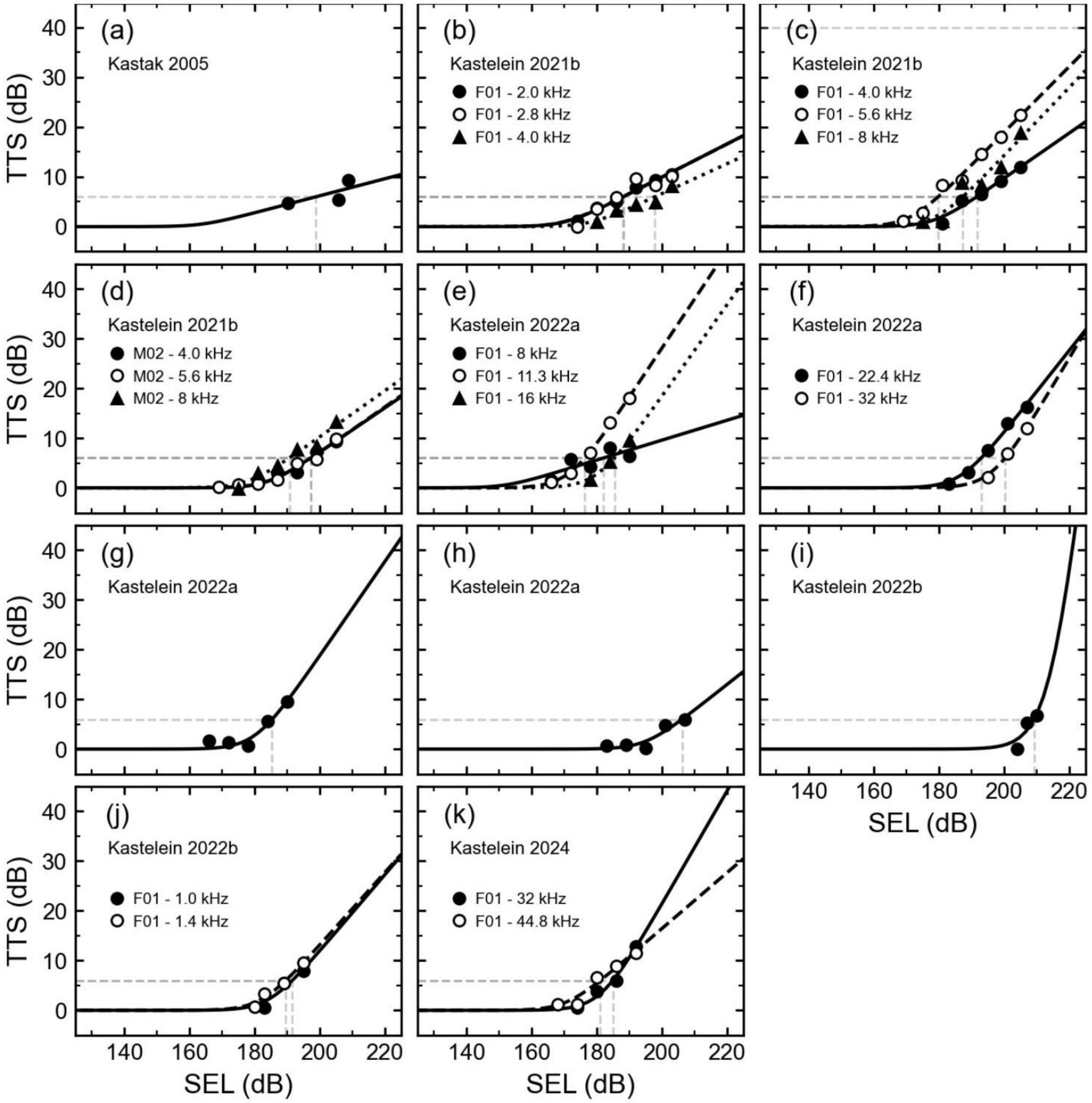
Figure C-3. TTS growth data for group OCA obtained using behavioral methods.

Table C-3. Summary of group OCA TTS growth data and onset exposure levels.

Group	Species	Study	Subject	Exp. Freq. (kHz)	Hear. Freq. (kHz)	Min TTS (dB)	Max TTS (dB)	TTS onset (dB SEL)	TTS growth rate (dB/dB)	INJ onset (dB SEL)	INJ-TTS offset (dB)	Notes	Panel
OCA	*Zalophus californianus*	Kastak 2007	Rio	2.5	2.5	0	24	159	2.4	176	18	-	(a)

TTS onset values are expressed in SEL, in dB re 20 $\mu Pa^2 s$.

Tests featured continuous exposure to steady-state noise and behavioral threshold measurements.



- Growth curves were obtained by fitting Eq. (6) to the TTS data as a function of SEL.
- Onset TTS was defined as the SEL value from the fitted curve at TTS $= 6$ dB, for only those datasets that bracketed 6 dB of TTS.
- Onset AINJ was defined as the SEL value from the fitted curve at a $TTS = 40$ dB, for only those datasets with maximum TTS > 20 dB.
- Solid lines are fit to the filled circles, dashed lines are fit to the open circles, and dotted lines fit to the triangles.
- See Table C-4 for explanation of the datasets in each panel. SEL units are dB re $1\ \mu\text{Pa}^2\text{s}$.

Figure C-4. TTS growth data for group OCW obtained using behavioral methods.

Table C-4. Summary of group OCW TTS growth data and onset exposure levels.

Group	Species	Study	Subject	Exp. Freq. (kHz)	Hear. Freq. (kHz)	Min TTS (dB)	Max TTS (dB)	TTS onset (dB SEL)	TTS growth rate (dB/dB)	INJ onset (dB SEL)	INJ-TTS offset (dB)	Notes	Panel
OCW	*Zalophus californianus*	Kastak 2005	Rio	2.5	2.5	4.8	9.3	199**	0.17	-	-		(a)
		Kastelein 2021b	F01	2	2	1.2	10	188**	0.33	-	-	Lower TTS onset at 2.8 kHz	(b)
				2	2.8	0	10	188	0.33	-	-	-	(b)
				2	4	0.9	8.2	198**	0.3	-	-	Lower TTS onset at 2.8 kHz	(b)
				4	4.2	0.6	12	192**	0.45	-	-	Lower TTS onset at 5.6 kHz	(c)
				4	5.6	1.2	22	180	0.66	232	52	-	(c)
				4	8	1	19	187**	0.68	-	-	Lower TTS onset at 5.6 kHz	(c)
			M02	4	4.2	1	9.4	197**	0.45	-	-	TTS measured 12-16 min post-exposure	(d)
				4	5.6	0.2	9.8	197**	0.46	-	-	TTS measured 12-16 min post-exposure	(d)
				4	8	0	13	191**	0.46	-	-	TTS measured 12-16 min post-exposure	(d)

Table C-4. Summary of group OCW TTS growth data and onset exposure levels. (Continued)

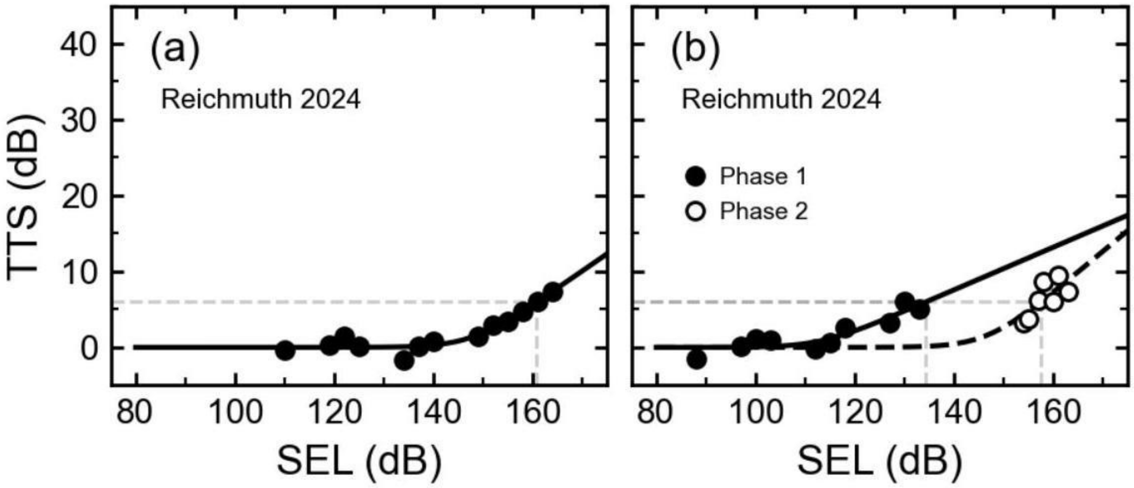
Group	Species	Study	Subject	Exp. Freq. (kHz)	Hear. Freq. (kHz)	Min TTS (dB)	Max TTS (dB)	TTS onset (dB SEL)	TTS growth rate (dB/dB)	INJ onset (dB SEL)	INJ-TTS offset (dB)	Notes	Panel
OCW	*Zalophus californianus*	Kastelein 2022a	F01	8	8	1.5	8	182**	0.2	-	-	Lower TTS onset at 11.3 kHz	(e)
				8	11.3	1.2	18	176	0.98	-	-	-	(e)
				8	16	1.7	9.5	186**	0.92	-	-	Lower TTS onset at 11.3 kHz	(e)
				16	22.4	0.8	16	193	0.83	-	-	-	(f)
				16	32	2.2	12	200**	1.1	-	-	Lower TTS onset at 22.4 kHz	(f)
			M02	8	11.3	0.7	9.5	185**	0.95	-	-	TTS measured 12-16 min post-exposure	(g)
				16	22.4	0.2	6	206**	0.52	-	-	TTS measured 12-16 min post-exposure	(h)
		Kastelein 2022b	F01	0.6	0.85	0.1	6.7	209	5.7	-	-	-	(i)
				1	1	0.5	8	192**	0.77	-	-	Lower TTS onset at 1.4 kHz	(j)
				1	1.4	0.7	9.6	190	0.73	-	-	-	(j)

Table C-4. Summary of group OCW TTS growth data and onset exposure levels. (Continued)

Group	Species	Study	Subject	Exp. Freq. (kHz)	Hear. Freq. (kHz)	Min TTS (dB)	Max TTS (dB)	TTS onset (dB SEL)	TTS growth rate (dB/dB)	INJ onset (dB SEL)	INJ-TTS offset (dB)	Notes	Panel
OCW	*Zalophus californianus*	Kastelein 2024	F01	32	32	0.6	13	185**	1.1	-	-	Lowest TTS onset at 44.8 kHz	(k)
				32	44.8	1.2	12	181	0.56	-	-	-	(k)

Only those data from which growth curves could be generated are included. TTS onset values are expressed in SEL, in dB re 1 $\mu Pa^2 s$. Tests featured continuous exposure to steady-state noise and behavioral threshold measurements. “Panel” refers to corresponding sub-panel plot within Figure C-4.

** Data excluded from mean onset TTS calculation. 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) a lower TTS onset was found at a different hearing test frequency (also see Notes).



Growth curves were obtained by fitting Eq. (6) to the TTS data as a function of SEL.

Onset TTS was defined as the SEL value from the fitted curve at TTS $= 6$ dB, for only those datasets that bracketed 6 dB of TTS.

Solid lines are fit to the filled circles, dashed lines are fit to the open circles.

See Table C-5 for explanation of the datasets in each panel.

SEL units are dB re $20\ \mu\mathrm{Pa}^2\mathrm{s}$.

Figure C-5. TTS growth data for group PCA obtained using behavioral methods.

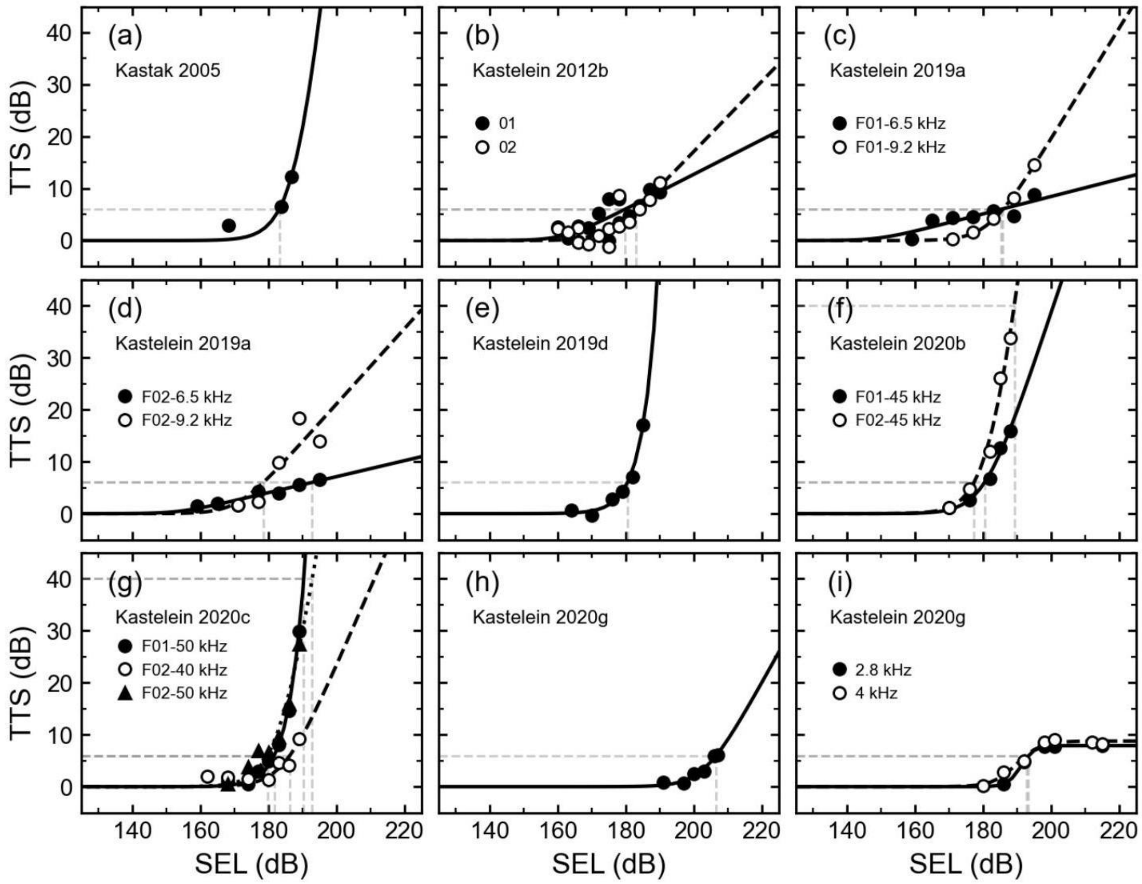
Table C-5. Summary of group PCA TTS growth data and onset exposure levels.

Group	Species	Study	Subject	Exp. Freq. (kHz)	Hear. Freq. (kHz)	Min TTS (dB)	Max TTS (dB)	TTS onset (dB SEL)	TTS growth rate (dB/dB)	INJ onset (dB SEL)	INJ-TTS offset (dB)	Notes	Panel
PCA	*Mirounga angustirostris*	Reichmuth 2024	Burnyce	1	1	0	7.4	161*	0.45	-	-	Data averaged by SEL. Much higher TTS onset than harbor seal at nearby frequency	(a)
	Phoca vitulina	Reichmuth 2024	Sprouts	2.5	2.5	0	6	134	0.28	-	-	Phase 1. Data averaged by SEL	(b)
				2.5	2.5	3.2	9.5	158**	0.55	-	-	Phase 2. Data averaged by SEL. Lower TTS onset during Phase 1 testing	(b)

Only those data from which growth curves could be generated are included. TTS onset values are expressed in SEL, in dB re $(20\ \mu\text{Pa}^2\text{s}$. Tests featured exposure to steady-state noise and behavioral threshold measurements. "Panel" refers to corresponding sub-panel plot within Figure C-5.

*SELs not used during exposure function fitting process.

** Data excluded from mean onset TTS calculation. 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) a lower TTS onset was found at a different hearing test frequency (also see Notes).



Growth curves were obtained by fitting Eq. (6) or (7) to the TTS data as a function of SEL.

Onset TTS was defined as the SEL value from the fitted curve at TTS = 6 dB, for only those datasets that bracketed 6 dB of TTS.

Onset AINJ was defined as the SEL value from the fitted curve at a TTS $= 40$ dB, for only those datasets with maximum TTS > 20 dB.

Solid lines are fit to the filled circles, dashed lines are fit to the open circles, and the dotted line is fit to the triangles.

See Table C-6 for explanation of the datasets in each panel. SEL units are dB re $1\ \mu\mathrm{Pa}^2\mathrm{s}$.

Figure C-6. TTS growth data for group PCW obtained using behavioral methods.

Table C-6. Summary of group PCW TTS growth data and onset exposure levels.

Group	Species	Study	Subject	Exp. Freq. (kHz)	Hear. Freq. (kHz)	Min TTS (dB)	Max TTS (dB)	TTS onset (dB SEL)	TTS growth rate (dB/dB)	INJ onset (dB SEL)	INJ-TTS offset (dB)	Notes	Panel
PCW	*Phoca vitulina*	Kastak 2005	Sprouts	2.5	2.5	3	12	183	6.5	-	-	-	(a)
		Kastelein 2012b	Seal 01	4	4	0	9.9	180	0.33	-	-	-	(b)
			Seal 02	4	4	0	11	183**	0.68	-	-	TTS measured 12-16 min post-exposure	(b)
		Kastelein 2019a	F01	6.5	6.5	0.3	8.8	185**	0.17	-	-	TTS measured 12-16 min post-exposure	(c)
				6.5	9.2	0.3	15	186**	1.1	-	-	TTS measured 12-16 min post-exposure	(c)
			F02	6.5	6.5	1.5	6.5	193**	0.15	-	-	Lower TTS onset at 9.2 kHz	(d)
				6.5	9.2	1.6	18	178	0.73	-	-	-	(d)
		Kastelein 2019d	F01	16	22.4	0	17	181	8×10^3	-	-	-	(e)
		Kastelein 2020b	F01	32	45	1.1	16	180**	2	-	-	TTS measured 12-16 min post-exposure	(f)
			F02	32	45	1.2	34	177	5.5	189	12	-	(f)

Table C-6. Summary of group PCW TTS growth data and onset exposure levels. (Continued)

Group	Species	Study	Subject	Exp. Freq. (kHz)	Hear. Freq. (kHz)	Min TTS (dB)	Max TTS (dB)	TTS onset (dB SEL)	TTS growth rate (dB/dB)	INJ onset (dB SEL)	INJ-TTS offset (dB)	Notes	Panel
PCW	*Phoca vitulina*	Kastelein 2020c	F01	40	50	0.6	30	182**	43	190	8.6	TTS measured 12-16 min post-exposure	(g)
			F02	40	40	1.4	9.2	186**	1.5	-	-	Lower TTS onset at 50 kHz	(g)
				40	50	0.5	28	180	4.2	193	13	-	(g)
		Kastelein 2020g	F02	1	1.4	0.7	6.1	207*	1.2	-	-	-	(h)
				2	2.8	0.5	7.9	193**	-	-	-	Lower TTS onset at 4 kHz	(i)
				2	4	0.2	9.1	193*	-	-	-	—	(i)

Only those data from which growth curves could be generated are included. TTS onset values are expressed in SEL, in dB re $1\ \mu\mathrm{Pa}^2\mathrm{s}$. Tests featured exposure to steady-state noise and behavioral threshold measurements. "Panel" refers to corresponding sub-panel plot within Figure C-6.

* SELs not used during exposure function fitting process.

** Data excluded from mean onset TTS calculation. 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) a lower TTS onset was found at a different hearing test frequency (also see Notes).

APPENDIX D. STUDIES CONSIDERED BUT NOT USED

D.1. STRIPED DOLPHIN AND HARBOR PORPOISE ALARM STUDY

Kastelein et al. (2006a) exposed a striped dolphin (*Stenella coeruleoalba*) and a harbor porpoise to an experimental acoustic alarm with a set of 16 tones with fundamental frequencies between 9 and 15 kHz. SPLs in the pen ranging from 116 dB re 1 µPa (for the fundamental 11 kHz tone) to 138 dB re 1 µPa (for the third harmonic of the 11 kHz tone). While the harbor porpoise responded by increasing its distance from the source (e.g., remaining on the opposite side of the pen) and increasing its respiration rate, the striped dolphin did not significantly change its distance to the source or respiration rate. Since the stimuli was an intentional alarm, these data were not utilized in the derivation of the Phase 4 behavioral Response Criteria.

D.2. SEA WORLD PINGER BEHAVIORAL RESPONSE STUDY

To test and quantify the reactions of a variety of species to the presence of fishing gear, along with the efficacy of an acoustic alarm, Sea World researchers conducted a series of experiments where fishing gear was introduced both with and without a pinger (Bowles and Anderson 2012). The species tested included harbor seals (*Phoca vitulina*), California sea lions, Northern elephant seals (*Mirounga angustirostris*), bottlenose dolphins, Commerson's dolphins (*Cephalorhynchus commersonii*), and a Pacific white-sided dolphin (*Lagenorhynchus obliquidens*). A Dukane pinger with a fundamental frequency of 10 kHz was used, and the sound pressure level in the various enclosures was measured to be approximately 130 dB throughout, with a reduction to 124 dB in a side refuge pool available to the Commerson's dolphins. In the simulated fishing gear trials, each group was tested with a baseline of 30 min then 30 min of exposure either to just a fishing net or to a net with a pinger attached. The types of behavioral responses observed varied widely both within and across species. Harbor seals avoided the pinger or only conducted brief approaches to it or to the gillnet, and some animals hauled out while the pinger was active. California sea lions demonstrated initial startle responses and jumped out of the pool, but only briefly (24 – 330 s). They also exhibited agonistic behaviors towards the net and pinger, and only one animal approached the net with the pinger attached. Northern elephant seals were the least reactive species to the pinger, although this was partly due to spending at least 40 percent of trials already hauled out. Some animals startled or left the pool with the active pinger, but others approached and manipulated the net with the active pinger. On the other hand, Commerson's dolphins demonstrated the strongest response to the pinger with highly active surface behaviors (e.g., rooster tailing, fluke slaps, and bubble trails), rapid swimming, and chasing, and then moving to the refuge pool. Some of these behaviors increased with subsequent trials, and eventually the dolphins began moving to the refuge pool during baseline periods, in conditioned anticipation of the signal. The Pacific white-sided dolphin was exposed with the bottlenose dolphin group; group swimming moved from synchronous to erratic when the pinger was turned on, with fast swimming and some charging at the pinger. However, these behaviors subsided and returned to baseline states rapidly, and were far less extreme than the behavioral responses exhibited by the Commerson's dolphins. These data were not included in the derivation of the Phase 4 behavioral risk criteria because the stimulus was an acoustic deterrent device.

D.3. GRAY SEAL CONTROLLED EXPOSURE STUDIES

Götz and Janik (2011) exposed wild-caught gray seals (*Halichoerus grypus*) to a 1 kHz "startle" sound to investigate the signal characteristics associated with the triggering of the startle response. Animals were kept for a short time at the Sea Mammal Research Unit (SMRU) of St. Andrews, Scotland before being released. The seals were first exposed to received SPLs of 170 dB re 1 µPa, then to increasing SPLs from

140 to 180 dB re 1 µPa in 5 dB increments. Five out of the seven exposed animals responded initially at 170 dB re 1 µPa, then with a mean of 159 dB re 1 µPa, while two did not respond at all. During the study, the animals that responded began sensitizing to the sound and their responses included cessation of feeding and avoidance of the sound source.

Götz (2008) also conducted boat-based playbacks of a variety of signals, including the startle stimuli used for the captive study. While he did observe that the number of animals close to the boat (e.g., within ~ 80 m) decreased and the number of animals further from the boat (~80-100 m) increased from the pre-exposure period to the during-exposure period, there was no way of knowing if the same animals were observed during each period.

Although these data were included in Phase 3, since the signal used in Götz and Janik (2011) was intended to be aversive and elicit a startle response, these data were not included in Phase 4. While the results from Götz (2008) likely demonstrate avoidance of the sound source, the data could not be used for the quantitative derivation of the behavioral criteria because observed responses of individuals could not be correlated with specific received levels.

D.4. GRAY WHALE HIGH FREQUENCY SONAR CEE

Similar to the LFAS study conducted on gray whales off California, a ship with a high frequency sonar source (IMAPS sonar, 21-25 kHz upsweeps) was positioned in the pathway of southbound migrating gray whales along the California coast (Frankel and Stein 2021). The source was either turned on or off for periods ranging from one to six hours per day over 22 days. Migrating gray whales were tracked using theodolites, and their distance offshore was measured using a gridded coordinate system. Researchers determined that when the sonar was on, gray whales started traveling at a slightly slower speed and shifted slightly away from the source. The deflection in course was detectable at 2 km but not significant until the whales were 1 km away from the source. Therefore, while the response started around 148 dB re 1 µPa, a significant response did not occur until approximately 156 dB re 1 µPa. These data are important as they suggest gray whale hearing does extend over 20 kHz; however, the actual sensation level at that frequency is unknown, so we cannot determine if a response occurred when the sonar was just detectable or if it had to reach some threshold for the animals to deflect their path around the source. Because the data were aggregated and no distances or received levels for individual responses were included, these data were not utilized in the derivation of the Phase 4 behavioral criteria.

D.5. REACTIONS OF RIGHT WHALES TO ALARM SOUNDS

D. Nowacek et al. (2004) developed an alarm signal to be deployed from ships in order to alert north Atlantic right whales (*Eubalaena glacialis*) to their presence and help avoid ship strikes. Six whales were exposed to the alert stimulus, five whales were exposed to a silent control, seven whales were exposed to playbacks of right whale social vocalizations, and five whales were exposed to a vessel approach stimulus. Five of the six whales exposed to the alert signal responded, while none of the whales exposed to other scenarios responded. Animals that reacted prematurely ended foraging dives, swam at a shallow angle to the surface, and remained there exhibiting abnormal diving behavior for the duration of the exposure. These data were included in the derivation of the Phase 3 but were excluded in Phase 4 due to the stimuli being an intentional alarm.

D.6. ADDITIONAL KASTELEIN STUDIES USING ALARM STIMULI

At SEAMARCO, numerous studies have been conducted on the behavioral responses of harbor porpoises and harbor seals to acoustic deterrent devices or other alarm-type stimuli (e.g., Kastelein et al. 1995, 2000, 2006b, 2015g, 2015h, 2017d, 2017e). However, because these stimuli were implemented with the intent to elicit a response, they were excluded from analysis in the derivation of the Phase 4 behavioral criteria.

Table D-1. Details of studies considered but not included in Phase 4 Behavioral Response Criteria.

Study	Signal	Signal Frequency	Signal Duration	Signal Interval	Source Level (dB re 1 µPa @ 1m)
Bowles and Anderson 2013	Dukane pinger	10 – 80 kHz	400 ms	4 sec	130
Götz and Janik 2011	Tone	1 kHz	200 ms	1 min	170; 140-180
Frankel and Stein 2021	IMAPS sonar	21 – 25 kHz upsweep	20 – 80 ms	5 sec	215
Nowacek et al. 2004a	Alarm	Mix of tones and sweeps	1 – 2 sec	72 sec	173 (max)
Kastelein et al. 1995	MF Acoustic Alarm	2.5 – 17.5	0.275	115	115
Kastelein et al. 1995	MF Acoustic Alarm	2.5	0.275	119	119
Kastelein et al. 1995	HF Acoustic Alarm	11.3	0.3	4.3	130
Kastelein et al. 2000	HF Acoustic Alarm	11.3	0.3	4.3	130
Kastelein et al. 2000	MF Acoustic Alarm	2 – 3.5	0.8	2	90 – 100
Kastelein et al. 2006b	HF Acoustic Alarm	9 – 15	0.3	4	116 – 133
Kastelein et al. 2015g	Seal Scarer	5 – 44	5	500 – 600	77 – 139
Kastelein et al. 2015g	Seal Scarer	15	0.5	1 – 30	91 – 151
Kastelein et al. 2015h	Acoustic Deterrent	15	0.5	1 – 30	91 – 151
Kastelein et al. 2015e	ALARM	10 – 20	5	50 – 600	109 – 134
Kastelein et al. 2015e	ALARM	15	0.5	1 – 30	128 – 138
Kastelein et al. 2017d	Acoustic Deterrent	60 – 150	3 – 10	multiple	74 – 110
Kastelein et al. 2017e	seal scarer	0.2 – 20	multiple	multiple	134 – 160

APPENDIX E. BEHAVIORAL RESPONSES TO SONAR AND SONAR-LIKE SOURCES: ALL INDIVIDUALS INCLUDED

Table E-1. Details for all individuals included in Behavioral Response Functions to Sonar and Sonar-Like Sources.

Animal	Exposure	Description of Response	RL at Response (dB re 1 µPa)	Max RL Without a Response (dB re 1 µPa)	CPA before Response or Overall CPA for No Response (km)	Southall Severity	Significant Behavioral Response
Killer whales - 3S							
oo06_317s	LFAS upsweep	moderate avoidance and lasted the duration of the exposure	150		2.5	6	1
oo06_327s/t	MFAS upsweep	change in behavioral state from foraging to travel, which lasted longer than the duration of the exposure	139		0.7	7	1
oo08_149a	MFAS upsweep	brief/minor increase in call rate and change in speed were observed		142	1.5	3	0
oo08_149a	LFAS upsweep	brief/minor modification in vocal response		166	1.2	2	0
oo08_149a	MFAS upsweep	separation of a mother/calf pair, which lasted the duration of the exposure, including a change in direction of travel, a brief increase in travel speed, and an increase in vocalizations; all of these were likely after or concurrent with the mother/calf separation	152		0.4	8	1
oo_09144a/b	LFAS upsweep	avoidance response that lasted longer than the duration of the exposure, including a change in behavioral state from foraging to travel, as well as a change in group distribution, an increase in vocalizations, and an increase in travel speed	94.5		0.5	7	1
oo_09144a/b	MFAS upsweep	avoidance of the source which lasted the duration of or longer than the exposure period	94		0.7	6	1
oo_09144a/b	LFAS downsweep	avoidance of the sound source that lasted the duration of the exposure	164		0.5	6	1

Animal	Exposure	Description of Response	RL at Response (dB re 1 µPa)	Max RL Without a Response (dB re 1 µPa)	CPA before Response or Overall CPA for No Response (km)	Southall Severity	Significant Behavioral Response
Pilot whales - 3S							
gm08_150c	MFAS upsweep	moderate avoidance, lasted the duration of the exposure	115		0.3	6	1
gm08_150c	LFAS upsweep	increase in vocalizations, increased travel speed, and a minor change in the direction of travel		170	0.3	3	0
gm08_154d	MFAS upsweep	brief cessation of vocalizations and a briefly increased travel speed		152	0.23	0	0
gm08_159a	LFAS upsweep	brief change in direction of travel, and a reduced travel speed that lasted less than the duration of exposure		175	0.4	4-3	0
gm08_159a	MFAS upsweep	no response		159	0.27	0	0
gm09_138a	LFAS upsweep	brief decrease in travel speed and change in direction of travel which did not rise to the level of a response		172	0.35	4	0
gm09_138a	MFAS upsweep	minor change in direction of travel which did not rise to the level of a response		167	0.19	0	0
gm09_138a	LFAS downsweep	change in behavioral state from feeding to travel, lasted the duration of the exposure	145		0.08	6	1
gm09_156b	LFAS upsweep	cessation of feeding (cessation of deep dives) which lasted the duration of the exposure	152		0.3	6-7	1
gm09_156b	MFAS upsweep	brief change in direction of travel and a moderate change in dive behavior that did not last the duration of the exposure		156	0.32	4	0
gm09_156b	LFAS downsweep	moderate avoidance that lasted the duration of the exposure	159		0.09	6	1
Sperm whales - 3S							

Animal	Exposure	Description of Response	RL at Response (dB re 1 µPa)	Max RL Without a Response (dB re 1 µPa)	CPA before Response or Overall CPA for No Response (km)	Southall Severity	Significant Behavioral Response
sw08_152a	MFAS upsweep	moderate avoidance that lasted the duration of the exposure	128		1.9	6	1
sw08_152a	LFAS upsweep	moderate cessation of feeding that lasted the duration of the exposure, moderate change in vocal behavior	156		1.6	6	1
sw09_141a	LFAS upsweep	moderate avoidance of sound source that lasted the duration of the exposure.	158		0.6	6	1
sw09_141a	MFAS upsweep	moderate avoidance, increase in social sounds that represented a moderate change in vocalizations; these did not last the duration of the exposure		150	0.64	6	0
sw09_142a	LFAS upsweep	avoidance response, including moderate change in dive behavior, and moderate change in direction of travel	120		1.36	6	1
sw09_142a	MFAS upsweep	no response		146	1.8	0	0
sw09_142a	LFAS downsweep	change in behavioral state from foraging to travel to rest, and a moderate change in dive behavior; these lasted the duration of the exposure	141		0.78	6	1
sw09_160a	MFAS upsweep	no response		151	1.5	0	0
sw09_160a	LFAS upsweep	moderate change in dive behavior, and a change in behavioral state from foraging to travel; these lasted the duration of the exposure	161		0.7	6	1
sw09_160a	LFAS downsweep	brief avoidance at the closest point of approach, did not rise to the level of a response		166	0.5	4	0
Sw16_126a	LFAS CAS	no response		163.5	0.64	0	0
Sw16_126a	low LFAS	cessation of foraging, cessation of buzzes	115.6		7.55	6	1
Sw16_126a	normal LFAS	no response		163.7	2.9	0	0

Animal	Exposure	Description of Response	RL at Response (dB re 1 µPa)	Max RL Without a Response (dB re 1 µPa)	CPA before Response or Overall CPA for No Response (km)	Southall Severity	Significant Behavioral Response
Sw16_130a	low LFAS	minor change in movement		163.7	0.85	3	0
Sw16_130a	LFAS CAS	no response		159.38	4.4	0	0
Sw16_134b	LFAS CAS	minor vocal response		167.4	1.67	2	0
Sw16_134b	normal LFAS	no response		181.3	0.06	0	0
Sw16_134b	low LFAS	minor/moderate avoidance; less than duration of exposure		157.5	1.35	5	0
Sw16_135a	normal LFAS	minor avoidance, change in feeding/vocal behavior, group comp, less than duration of exposure		174.9	0.86	5	0
Sw16_135a	LFAS CAS	minor change in dive behavior and vocalization, less than duration of exposure		158.2	2.55	3	0
Sw16_135a	low LFAS	no response		172.8	0.047	0	0
Sw16_136a	LFAS CAS	no response		165.3	2.4	0	0
Sw16_136a	low LFAS	no response		163.5	1.09	0	0
Sw16_136a	normal LFAS	minor change in vocalization		179.05	0.41	2	0
Sw17_179a	low LFAS	minor change in vocalization		153.7	2.25	2	0
Sw17_179a	normal LFAS	no response		172.96	1.29	0	0
Sw17_179a	LFAS CAS	no response		166.5	1.3	0	0
Sw17_180a	normal LFAS	no response		172.3	1.3	0	0
Sw17_180a	low LFAS	minor change in orientation and vocalization		157.5	1.7	2	0
Sw17_180a	LFAS CAS	minor change in vocalization		152.1	5.7	2	0
Sw17_182a	low LFAS	moderate change in dive profile and change in behavior (stopped resting), change in behavior less than duration of exposure		116	36.2	6	0
Sw17_182a	LFAS CAS	no response		119.2	54.1	0	0
Sw17_182a	normal LFAS	minor change in vocalizations		130.2	62	2	0
Sw17_182b	low LFAS	no response		157.4	2.4	0	0

Animal	Exposure	Description of Response	RL at Response (dB re 1 µPa)	Max RL Without a Response (dB re 1 µPa)	CPA before Response or Overall CPA for No Response (km)	Southall Severity	Significant Behavioral Response
Sw17_182b	LFAS CAS	minor avoidance, brief change in dive profile and vocalizations, less than duration of exposure		160.03	2.3	5	0
Sw17_182b	normal LFAS	minor change in vocalizations		167	1.3	3	0
Sw17_184a	LFAS CAS	no response		154.8	2.9	0	0
Sw17_184a	normal LFAS	no response		157.3	4.75	0	0
Sw17_186a	normal LFAS	no response		130.2	62.1	0	0
Sw17_186a	LFAS CAS	no response		125.1	62.7	0	0
Sw17_186b	normal LFAS	no response		168.2	5.1	0	0
Sw17_186b	CAS signal	minor cessation of feeding, change in dive profile, orientation and vocalizations, also approached vessel; less than duration of exposure		173.8	0.06	5	0
Sw17_186b	low LFAS	no response		154.8	1.6	0	0
Sw17_188a	low LFAS	brief orientation response		156.4	1.3	1	0
Sw17_188a	normal LFAS	no response		163.5	5	0	0
Sw17_188a	LFAS CAS	minor change in dive behavior and vocalization		171.2	0.05	3	0
Sw17_188a	CAS signal	moderate change in dive behavior and vocalizations, less than duration of exposure		170.3	0.32	4	0
Sw17_191a	normal LFAS	moderate avoidance, change in dive behavior and cessation of foraging; less than duration of exposure	163		3.2	6	1
Sw17_191a	low LFAS	moderate avoidance, change in dive behavior and cessation of foraging, duration of exposure	146.7		0.8	6	1
sw19_241a	HPAS-C	cessation of feeding		145	7.7	5	0
sw19_241a	HPAS-D	vocal behavior		154.9	7.6	2	0
sw19_241a	MPAS-C	orientation		166	6.7	2	0
sw19_241b	HPAC-C	locomotion/dive/vocal		150	5	3	0
sw19_241b	HPAS-D	none		155.8	5.4	0	0
sw19_241b	MPAS-C	avoidance		167	6.8	5	0

Animal	Exposure	Description of Response	RL at Response (dB re 1 µPa)	Max RL Without a Response (dB re 1 µPa)	CPA before Response or Overall CPA for No Response (km)	Southall Severity	Significant Behavioral Response
sw19_243a	HPAS-D	vocal		160	2.6	2	0
sw19_243a	HPAS-C	avoidance		165	2.4	5	0
sw19_244a	XHPAS-D	none		151	23.8	0	0
sw19_244a	XHPAS-C	none		150	23.8	0	0
sw19_245a	XHPAS-D	cessation of feeding		186	3.2	5	0
sw19_245a	XHPAS-C	cessation of feeding	110.8		5.8	6	1
sw19_248b	HPAS-D	none		159.7	9.9	0	0
sw19_248b	MPAS-D	none		157.3	3.7	0	0
sw19_248b	HPAS-C	none		157	8.4	0	0
sw19_250a	XHPAS-C	orientation		160	2.26	1	0
sw19_250a	XHPAS-D	none		162.2	6.4	0	0
sw19_253c	XHPAS-D	none		172	5.1	0	0
sw19_253c	XHPAS-C	avoidance	145.2		2.2	5	1
sw19_254a	XHPAS-C	orientation		168	7.5	1	0
sw19_254a	HPASF-C	cessation of feeding		159	6.2	4	0
sw19_254a	XHPAS-D	avoidance	99.3		9.3	6	1
sw19_255b	XHPAS-D	none		171	5.2	0	0
sw19_255b	XHPAS-C	avoidance/dive	158.1		2.7	5	1
sw19_255d	XHPAS-D	none		151.9	1.5	0	0
sw19_255d	XHPAS-C	none		141.2	8.4	0	0
sw19_259b	XHPAS-C	avoidance	169.8		3.5	7	1
sw19_259b	XHPAS-D	avoidance/behavior	142		12.3	7	1
Humpback whales - 3S							
mn11_157	Sonar1	brief avoidance when the animal turned away from the source, but was back again at the next sighting		164	0.96	4	0

Animal	Exposure	Description of Response	RL at Response (dB re 1 µPa)	Max RL Without a Response (dB re 1 µPa)	CPA before Response or Overall CPA for No Response (km)	Southall Severity	Significant Behavioral Response
mn11_157	Sonar2	No response		177	0.06	0	0
mn11_160	Sonar1	No response		174	0.21	0	0
mn11_160	Sonar2	No response		168	0.51	0	0
mn11_165	Sonar1	No response		176	0.24	0	0
mn11_165	Sonar2	minor change locomotion was observed when the animal made a sharp turn, but was not considered avoidance		176	0.2	3	0
mn12_161	Sonar1	moderate change in dive profile and moderate avoidance that included an increase in speed and a change in direction away from the source that lasted the duration of the exposure	133		0.3	6	1
mn12_161	Sonar2	brief change in dive profile that only lasted for one dive then returned to normal during the exposure		159	0.1	2	0
mn12_164	Sonar1	moderate cessation of feeding just after the onset of sonar, and an extended change in dive profile from deep to shallow dives	125		0.83	5-6	1
mn12_164	Sonar2	minor change in locomotion and a cessation of lunging coincided during the first dive of the exposure		170	0.02	3-4	0
mn12_170	Sonar1	No response		174	0.3	0	0
mn12_170	Sonar2	minor avoidance that did not last the duration of the exposure		172	0.43	5	0

Animal	Exposure	Description of Response	RL at Response (dB re 1 µPa)	Max RL Without a Response (dB re 1 µPa)	CPA before Response or Overall CPA for No Response (km)	Southall Severity	Significant Behavioral Response
mn12_171	Sonar1	minor change in dive profile from deep feeding dives to shallow dives and a minor cessation of feeding concurrent with that change		179	0.19	3,5	0
mn12_171	Sonar2 (no ramp up)	moderate cessation of feeding observed, but it did not last the duration of the exposure		182	0.06	6	0
mn12_178	Sonar1	brief avoidance away from the source, but it was difficult to determine whether this turn was in response to sonar, and did not last the duration of the exposure		174	0.48	4	0
mn12_178	Sonar2 (no ramp up)	No response		174	0.25	0	0
mn12_179	Sonar1	brief change in dive profile		173	0.33	2	0
mn12_179	Sonar2 (no ramp up)	minor change in dive profile and a minor change in locomotion, with changes in direction and speed		176	0.11	3,3	0
mn12_180	Sonar1	moderate change in dive profile and moderate cessation of feeding that lasted longer than the duration of the exposure	165		0.4	4,6	1
mn12_180	Sonar2 (no ramp up)	moderate avoidance that lasted longer than the duration of the exposure	127		0.26	6	1
Minke whale - 3S							
ba11_180	Sonar1	prolonged avoidance that lasted greater than the duration of the exposure; this response might also have involved a cessation of feeding. There was also obvious aversion and sensitization, as shown by a further change in dive pattern and increase in travel speed away from the source during the avoidance	146		4.5	7	1
Bottlenose whale - 3S							

Animal	Exposure	Description of Response	RL at Response (dB re 1 µPa)	Max RL Without a Response (dB re 1 µPa)	CPA before Response or Overall CPA for No Response (km)	Southall Severity	Significant Behavioral Response
Ha13_176a	LFAS	avoidance, cessation of foraging, cessation of vocal behavior	130		4.4	7.5	1
Ha15_179b	LFAS	prolonged avoidance, cessation, of foraging, cessation of vocal behavior	127.2		0.81	7	1
Ha16_170a	MFAS	cessation of foraging, change in dive and vocal behavior, later prolonged avoidance	117		16.8	7.5	1
Ha15_171a	LFAS	moderate cessation of foraging that lasted beyond exposure duration, but animal approached and circled active vessel	69.5	98.7	0.2	6	0
Blue whales - SOCAL BRS							
bw10_235a	MFAS	decrease in body acceleration, but this was not outside normal behavior for this animal		165	0.65	0	0
bw10_235b	MFAS	No response		143	0.85	0	0
bw10_238a	MFAS	No response		143	0.2	0	0
bw10_239b	MFAS	change in feeding behavior, a minor cessation of feeding, and an increase in speed but not avoidance, and none of these responses lasted the duration of the exposure		159	2.8	5-6	0
bw10_240a	MFAS	No response		163	0.5	0	0
bw10_240b	MFAS	No response		154	3.7	0	0
bw10_246a	MFAS	No response		159	1.5	0	0
bw10_246b	MFAS	No response		161	1.3	0	0
bw10_265a	MFAS	No response		155	1.9	0	0
bw10_266a	MFAS	cessation of feeding; this lasted longer than the duration of the exposure	146		1.3	7	1
bw11_210a	MFAS	No response		161	1.2	0	0

Animal	Exposure	Description of Response	RL at Response (dB re 1 µPa)	Max RL Without a Response (dB re 1 µPa)	CPA before Response or Overall CPA for No Response (km)	Southall Severity	Significant Behavioral Response
bw11_210b	MFAS	cessation of feeding, an increase in speed leading to avoidance, and a change in dive behavior; these lasted the duration of the exposure	117		0.8	6-7	1
bw11_213b	MFAS	No response		160	0.8	0	0
bw11_219b	MFAS	decrease in MSA, a change in heading, and a change in feeding behavior prior to start of exposure, during the exposure there was a change in dive behavior that did not last the duration of the exposure		155	0.25	3-4	0
bw11_220b	MFAS	moderate cessation of feeding, with a longer surface series, along with minor avoidance and a minor change in dive behavior; however, the animal returned to feeding during the exposure		136	1.2	5-6	0
bw13_191a	Real MFAS	increase in foraging behavior		146	10	0	0
bw13_259a	MFAS	No response		127	4.5	0	0
bw14_218a	MFAS	minor cessation of feeding, minor change in locomotion		116	1.1	4.5	0
bw14_211b	MFAS	minor cessation in foraging, moderate change in locomotion		146	0.7	4.5	0
bw14_262b	MFAS	minor change in locomotion		137	1.4	3.0	0
bw14_262a	MFAS	no response		137	1.4	0.0	0
bw14_256a	MFAS	prolonged cessation of foraging, minor avoidance	111		0.8	6.0	1
bw16_264b	Real MFAS	no response		147	13	0.0	0
20160918-B008-BM	Real MFAS	no response		<100	232	0.0	0
20160817-B021-BM	helo-dip MFAS	moderate cessation of feeding, avoidance of source, change in dive behavior	143		8.1	6	1
20160817-B021-BM	helo-dip MFAS	minor avoidance of source and cessation of feeding		141.4	8	5.0	0

Animal	Exposure	Description of Response	RL at Response (dB re 1 µPa)	Max RL Without a Response (dB re 1 µPa)	CPA before Response or Overall CPA for No Response (km)	Southall Severity	Significant Behavioral Response
bw_193a	Real MFAS	no response		148	18	0.0	0
bw_231b	helo-dip MFAS	minor change in dive profile		141	5	0.0	0
Fin whales - SOCAL BRS							
bp10_229a	MFAS	no response		148	2	0.0	0
bp13_216a	MFAS	no response		153	1.2	0.0	0
bp13_257b	MFAS	brief avoidance		129	1.2	4.0	0
2016-0912-B014-Bp	MFAS	no response		156	3.06	0.0	0
bp10_236a	MFAS	no response		153	4.5	0.0	0
bp10_236b	MFAS	minor brief avoidance		161	0.8	4.0	0
bp13_259a	MFAS	no response		153	1.77	0.0	0
bp16_256a	MFAS	no response		156	1.5	0.0	0
bp13_139a	MFAS	no response		138	1.3	0.0	0
bp10_239a	MFAS	minor change in dive profile		160	1.1	1.5	0
bp15_236a	MFAS	no response		151	1	0.0	0
bp_075a	Real MFAS	no response		130.5	50	0.0	0
bp_193a	Real MFAS	mod change in locomotion, no avoidance		110	71	0.0	0
Risso's dolphins - SOCAL BRS							
gg13_190a	Real MFAS	no response		131	80	0.0	0
gg13_213a	Real MFAS	no response		128	60	0.0	0
Beaked whales - SOCAL BRS							

Animal	Exposure	Description of Response	RL at Response (dB re 1 µPa)	Max RL Without a Response (dB re 1 µPa)	CPA before Response or Overall CPA for No Response (km)	Southall Severity	Significant Behavioral Response
zc10_272a	MFAS	moderate/prolonged cessation of clicking (indicative of foraging), moderate/ sustained avoidance and an increase in speed and body acceleration as well as a change in direction, these lasted longer than the duration of the exposure	98		1.5	6.5	1
bb12_214a	MFAS	increase in speed, a change in heading, and possible moderate avoidance, and a change in depth/dive behavior at start of exposure, but the animal resumed foraging during the exposure therefore this did not rise to the level of a response.	100		2.7	6	1
zc11_267a	MFAS	prolonged cessation of feeding and sustained avoidance which lasted longer than the duration of the response	95		1	6.5	1
zc13_210a	Incidental MFAS	No response		116	60	0	0
zc13_210a	Real MFAS	No response		124	83	0	0
Fin whales - SURTASS LFA							
Fin whale 1	LFAS	No response		148	NA	0	0
Fin whale 2	LFAS	No response		148	NA	0	0
Fin whale 3	LFAS	No response		148	NA	0	0
Fin whale 4	LFAS	No response		148	NA	0	0
Fin whale 5	LFAS	No response		148	NA	0	0
Blue whale - SURTASS LFA							
Blue whale 1	LFAS	No response		150	NA	0	0
Humpback whales - SURTASS LFA							

Animal	Exposure	Description of Response	RL at Response (dB re 1 µPa)	Max RL Without a Response (dB re 1 µPa)	CPA before Response or Overall CPA for No Response (km)	Southall Severity	Significant Behavioral Response
Singer 1	LFAS	cessation of song vocalizations; this lasted as long as or longer than the duration of the exposure		132	4.3	3	0
Singer 2	LFAS	cessation of song vocalizations; this lasted as long as or longer than the duration of the exposure		142	0.5	3	0
Singer 3	LFAS	cessation of song vocalizations; this lasted as long as or longer than the duration of the exposure		121	<11.3	3	0
Singer 4	LFAS	cessation of song vocalizations; this lasted as long as or longer than the duration of the exposure		126	<6.7	3	0
Singer 5	LFAS	Response was cessation of song vocalizations; this lasted as long as or longer than the duration of the exposure.		122	4.5	3	0
Singer 6	LFAS	Response was cessation of song vocalizations; this lasted as long as or longer than the duration of the exposure.		138	0.5	3	0
Singer 7	LFAS	stopped vocalizing during the sonar playback, however they joined with other animals and therefore the change was not in response to sonar		124	5.2	0	0
Singer 8	LFAS	stopped vocalizing during the sonar playback, however they joined with other animals and therefore the change was not in response to sonar		133	1	0	0
Singer 9	LFAS	stopped vocalizing during the sonar playback, however they joined with other animals and therefore the change was not in response to sonar		137	1.2	0	0
Singer 10	LFAS	stopped vocalizing during the sonar playback, however they joined with other animals and		122	8	0	0

Animal	Exposure	Description of Response	RL at Response (dB re 1 µPa)	Max RL Without a Response (dB re 1 µPa)	CPA before Response or Overall CPA for No Response (km)	Southall Severity	Significant Behavioral Response
		therefore the change was not in response to sonar					
Singer 11	LFAS	did not stop vocalizing during the sonar playback, therefore no response was observed		124	6.7	0	0
Singer 12	LFAS	did not stop vocalizing during the sonar playback, therefore no response was observed		150	1.3	0	0
Singer 13	LFAS	did not stop vocalizing during the sonar playback, therefore no response was observed		150	0.4	0	0
Singer 14	LFAS	did not stop vocalizing during the sonar playback, therefore no response was observed		140	7.4	0	0
Singer 15	LFAS	did not stop vocalizing during the sonar playback, therefore no response was observed		129	3.8	0	0
Singer 16	LFAS	did not stop vocalizing during the sonar playback, therefore no response was observed		132	16.6	0	0
Singer 17	LFAS	did not stop vocalizing during the sonar playback, therefore no response was observed		133	7.3	0	0
Bottlenose dolphins - CES							
Dolphin 1	MFAS	No response		115	0.01	0	0
Dolphin 2	MFAS	Minor change in respiration rate on one trial	115		0.01	3	0
Dolphin 3	MFAS	Minor change in respiration rate on one trial	115		0.01	3	0
Dolphin 4	MFAS	No response		115	0.01	0	0
Dolphin 5	MFAS	No response		115	0.01	0	0
Dolphin 6	MFAS	No response		130	0.01	0	0
Dolphin 7	MFAS	Minor change in respiration rate on two trials	130		0.01	3	0
Dolphin 8	MFAS	refusal to participate on tenth trial, minor change in respiration on one trial	130		0.01	7	1

Animal	Exposure	Description of Response	RL at Response (dB re 1 µPa)	Max RL Without a Response (dB re 1 µPa)	CPA before Response or Overall CPA for No Response (km)	Southall Severity	Significant Behavioral Response
Dolphin 9	MFAS	Minor change in respiration rate on nine trials	130		0.01	3	0
Dolphin 10	MFAS	No response		130	0.01	0	0
Dolphin 11	MFAS	Minor change in respiration rate on one trial	145		0.01	3	0
Dolphin 12	MFAS	fluke slaps on two trials	145		0.01	6	1
Dolphin 13	MFAS	refusal to participate on tenth trial	145		0.01	7	1
Dolphin 14	MFAS	No response		145	0.01	0	0
Dolphin 15	MFAS	Minor change in respiration rate on two trials	145		0.01	3	0
Dolphin 16	MFAS	Minor change in respiration rate on one trial	160		0.01	3	0
Dolphin 17	MFAS	Minor change in respiration rate on one trial	160		0.01	3	0
Dolphin 18	MFAS	No response		160	0.01	0	0
Dolphin 19	MFAS	refusal to participate on first trial	160		0.01	7	1
Dolphin 20	MFAS	Minor change in respiration rate on one trial	160		0.01	3	0
Dolphin 21	MFAS	Minor change in respiration rate on one trial	175		0.01	3	0
Dolphin 22	MFAS	refusal to participate on three trials and fluke slaps on six trials, minor changes in respiration	175		0.01	7	1
Dolphin 23	MFAS	refusal to participate on all trials	175		0.01	7	1
Dolphin 24	MFAS	refusal to participate on seven trials, minor change in respiration on nine trials	175		0.01	7	1
Dolphin 25	MFAS	Minor change in respiration rate on one trial	175		0.01	3	0
Dolphin 26	MFAS	refusal to participate all trials	185		0.01	7	1
Dolphin 27	MFAS	refusal to participate all trials	185		0.01	7	1
Dolphin 28	MFAS	refusal to participate all trials	185		0.01	7	1
Dolphin 29	MFAS	refusal to participate all trials	185		0.01	7	1
Dolphin 30	MFAS	refusal to participate all trials	185		0.01	7	1

Animal	Exposure	Description of Response	RL at Response (dB re 1 µPa)	Max RL Without a Response (dB re 1 µPa)	CPA before Response or Overall CPA for No Response (km)	Southall Severity	Significant Behavioral Response
California sea lions - CES							
Sea Lion 1	MFAS	refusal to participate on four trials, minor changes in duration of submergence and respiration rate throughout trials	125		0.01	7	1
Sea Lion 2	MFAS	Minor change in respiration on three trials	125		0.01	3	0
Sea Lion 3	MFAS	Minor change in respiration on three trials	125		0.01	3	0
Sea Lion 4	MFAS	refusal to participate on two trials	140		0.01	7	1
Sea Lion 5	MFAS	No response		140	0.01	0	0
Sea Lion 6	MFAS	No response		140	0.01	0	0
Sea Lion 7	MFAS	haul out on five trials and refusal to participate on remaining five trials	155		0.01	9	1
Sea Lion 8	MFAS	Minor change in respiration rate on four trials	155		0.01	3	0
Sea Lion 9	MFAS	Minor change in respiration rate on three trials	155		0.01	3	0
Sea Lion 10	MFAS	haul out on eight trials and refusal to participate on remaining two trials	170		0.01	9	1
Sea Lion 11	MFAS	refusal to participate on seven trials, minor change in respiration rate on nine trials, increase in submergence time throughout	170		0.01	7	1
Sea Lion 12	MFAS	haul out on one trial and refuse to participate on remaining eight trials, minor change in respiration rate on nine trials	170		0.01	9	1
Sea Lion 13	MFAS	haul out on five trials and refusal to participate on five trials	185		0.01	9	1
Sea Lion 14	MFAS	refusal to participate on all trials	185		0.01	7	1
Sea Lion 15	MFAS	refusal to participate on two trials, minor increase in respiration rate on two trials	185		0.01	7	1

Animal	Exposure	Description of Response	RL at Response (dB re 1 µPa)	Max RL Without a Response (dB re 1 µPa)	CPA before Response or Overall CPA for No Response (km)	Southall Severity	Significant Behavioral Response
Hooded seals - CES							
Hooded seal 1	MFAS	active avoidance of sound source, reduced dive activity, and floating with head out of water	160		NA	6	1
Hooded seal 2	MFAS	active avoidance of sound source, reduced dive activity, and floating with head out of water	163		NA	6	1
Hooded seal 3	MFAS	active avoidance of sound source, reduced dive activity, and floating with head out of water	166		NA	6	1
Hooded seal 4	MFAS	active avoidance of sound source, reduced dive activity, and floating with head out of water	169		NA	6	1
Kastelein Harbor Porpoise Studies							
kas_02	LFAS	respiration		114	0.003	3	0
kas_02	LFAS_DS	respiration		114	0.003	3	0
kas_02	MFAS	avoidance		107	0.003	4	0
kas_02	MFAS_DS	avoidance		107	0.003	4	0
kas_02	LFAS	avoidance	123		0.003	4	1
kas_02	LFAS_DS	respiration		123	0.003	3	0
kas_03	MFAS	avoidance	106		0.003	4	1
kas_06	MFA HELO	increased surfacings		98	0.003	3	0
kas_07	MFA HELO	brief response		144	0.003	3	0
kas_08	MFAS CAS	none		143	0.003	0	0
kas_08	MFA	none		143	0.003	0	0
kas_09	MFAS CAS	avoidance	143		0.003	6	1
kas_09	MFA	none		143	0.003	0	0
kas_12	HFAS	avoidance	113		0.003	6	1
kas_14	HFAS	jumping	125		0.003	7	1
kas_14	HFAS	jumping	118		0.003	7	1

Animal	Exposure	Description of Response	RL at Response (dB re 1 µPa)	Max RL Without a Response (dB re 1 µPa)	CPA before Response or Overall CPA for No Response (km)	Southall Severity	Significant Behavioral Response
kas_14	HFAS	jumping	136		0.003	7	1
kas_18	HFAS	faster swimming	131		0.003	5	1
kas_18	HFAS	avoidance	125		0.003	6	1
Kastelein Harbor Seal Studies							
PV_01	HFAS	avoidance	108		0.003	6	1
PV_02	HFAS	avoidance	107		0.003	6	1
PV_03	HFAS	avoidance	107		0.003	6	1
PV_04	HFAS	avoidance	108		0.003	6	1
PV_05	MFAS	avoidance	141		0.003	6	1
PV_06	HFAS	avoidance	133		0.003	6	1
PV_07	HFAS	avoidance	135		0.003	6	1
PV_08	HFAS	avoidance	141		0.003	6	1
PV_13	HFAS	jumping	158		0.003	6	1
PV_14	HFAS	faster swimming, head out		156	0.003	4	0
PV_15	HFAS	none		156	0.003	0	0

APPENDIX F. SUMMARIES OF STUDIES ON BEHAVIORAL RESPONSES TO SEISMIC SURVEYS

Table F-1. Summaries of Studies on Behavioral Responses to Seismic Surveys.

Reference	Subjects	Description of Response	Context	RL at Response	Max RL Without a Response	Distance at Response or No Response (km)	Latency to Return to Baseline (after seismic ceased)
Bowhead Whales							
Koski & Johnson (1987)	Group (n=4-7)	"Strong avoidance response;" swam rapidly away from the operating seismic vessel, shorter dives, longer duration at surface, more blows.	Migrating	137 dB re 1 µPa	117 dB re 1 µPa	24	NA
Ljungblad et al. (1988)	Group 1 (n=8)	Milling and socializing behaviors increased while traveling, surfacing and dive times decreased. Overt behavioral changes (i.e., tail slapping, startle responses, and avoidance behavior), most whales traveled away at medium to fast speeds, fewer blows per surfacing, longer blow intervals.	Milling, socializing, traveling at slow to medium speeds	142 dB re 1 µPa	131 dB re 1 µPa	3.5	NA
Ljungblad et al. (1988)	Group 2 (n=3)	Abrupt change of behavior which included considerable water disturbance, tail slaps, sudden travel at moderate to fast speed away from the approaching vessel, significant increase in blow interval, fewer blows per surfacing, shorter surfacing and dive durations.	Milling, socializing, traveling at slow speeds	164.6 dB re 1 µPa	NA	7.2	30-60 minutes

Reference	Subjects	Description of Response	Context	RL at Response	Max RL Without a Response	Distance at Response or No Response (km)	Latency to Return to Baseline (after seismic ceased)
Ljungblad et al. (1988)	Group 3 (n=7)	Avoidance behavior; two whales ceased milling and diving, turned from the approaching vessel and swam away rapidly. Length of surfacing increased slightly, and number of blows per surfacing decreased.	Milling, socializing, traveling at slow to medium speeds, occasional feeding	171.2 dB re 1 µPa	154.9 dB re 1 µPa	5	30-60 minutes
Ljungblad et al. (1988)	Group 4 (n=50)	Traveling at slow, medium or fast speeds; calves surface behaviors (rolling, touching, flipper slapping) increase in mother-calf cohesion. Avoidance behavior; two groups of whales (n=7 and 2 mother-calf pairs) move away from source.	Milling, socializing, traveling at slow to medium speeds	158 dB re 1 µPa	154 dB re 1 µPa	7.6	30-60 minutes
Miller et al. (2005)	166 Groups (n=259)	Avoided vessel 600 m further with seismic than without seismic; reduced sighting rates when seismic activity was occurring, increased sighting distances from the vessel indicating some whales avoided much farther. Apart from displacement, behaviors were similar to non-seismic periods.	Summer feeding grounds	170 dB re 1 µPa (rms)	150 dB re 1 µPa (rms)	1.9 (average)	NA
Richardson et al (1999)	Multiple Groups	Avoided the area within 20-30 km of source; bowheads were common on days without seismic.	Migrating	120 - 130 dB re 1 µPa (rms over pulse duration)	NA	20	Next day without seismic
Blackwell et al. (2013)	Multiple Individuals	Vocal behavior (call rate) decreased near the activity, call rates remain unchanged far from the activity (> 104 km).	Migrating	116 - 129 dB re 1 µPa (SPL)	108 dB re 1 µPa (SPL)	41	NA

Reference	Subjects	Description of Response	Context	RL at Response	Max RL Without a Response	Distance at Response or No Response (km)	Latency to Return to Baseline (after seismic ceased)
Blackwell et al. (2015)	Multiple Individuals	Whales ceased vocal behavior ("virtually silent").	Migrating	> 160 dB re 1 µPa^{2}s (142 dB re 1 µPa^{2}s single-pulse SEL)	< 92 dB re 1 µPa^{2}s	10 - 40	NA
Richardson et al. (1985)	10 Groups (n=1-14)	No clear avoidance behaviors; subtle alterations in surfacing, respiration, and diving behaviors.	Feeding grounds (skim feed), socializing, mud churning, log play, slow travel, nursing	NA	150 dB re 1 µPa	6	NA
Richardson et al. (1985)	10 Groups (n=1-14)	Echelon sizes reduced and whales did not vocalize for entire 20-min period. Reduced duration of surfacings, dives and number of bows, but not significantly.	Echelon feeding	118 dB re 1 µPa	NA	5	< 2 hours
Richardson et al. (1985)	10 Groups (n=1-14)	Blow intervals significantly increased. Reduced duration of surfacings, dives and number of bows, but not significantly.	Diving with gradual travel	123 dB re 1 µPa	NA	3	NA
Richardson et al. (1986)	21 Groups	No clear avoidance behaviors; subtle alterations in surfacing, respiration, and diving behaviors (e.g., significantly fewer blows per surfacing).	Bottom-feeding, socializing, mud churning, log play, travel, nursing, vocalizing	NA	107 dB re 1 µPa	6	NA
Richardson et al. (1986)	Multiple Individuals (n=6)	Whales ceased bottom-feeding, reduced diving, decreased blow interval; two identifiable whales swam 2 km away from source. Orientations of whales at surface were indicative of avoidance.	Traveling slow to medium speed at surface, bottom-feeding	> 170 dB re 1 µPa	< 160 dB re 1 µPa	3	NA

Reference	Subjects	Description of Response	Context	RL at Response	Max RL Without a Response	Distance at Response or No Response (km)	Latency to Return to Baseline (after seismic ceased)
Richardson et al. (1986)	Multiple Individuals	Some whales orient away from the source, but some continue bottom-feeding.	Skim feeding in echelon formation	124 - 134 dB re 1 µPa	133 dB re 1 µPa	2 - 4.5	NA
Gray Whales							
Malme et al. (1984)	Multiple Individuals	Avoidance behavior; changed course out to 3 km.	Migrating	164 dB re 1 µPa (pp)	NA	NA	NA
Malme et al. (1986)	Whale E	Stopped feeding and changed direction or speed of movement away from the source. Most gray whales returned to the area and resumed feeding once the airgun stopped.	Feeding	149	NA	4	Soon after airgun vessel passed
Malme et al. (1986)	Whale A	Stopped feeding, changed direction, and did not return / continued moving out of the area.	Feeding	154.5	NA	< 4	NA
Malme et al. (1988)	Whale B	Changed orientation, increased speed, dove with fluke out, and then resumed feeding.	Feeding	176.5	NA	0.18	Immediately
Malme et al. (1988)	Whale L	Spyhop and travel.	Feeding	169	NA	1	NA
Malme et al. (1988)	Whale N	Joined whale L, then swam parallel to seismic vessel alone and traveled offshore.	Feeding	> 170 dB (peak)	NA	< 0.1	Soon after airgun vessel passed
Gailey et al. (2016)	Whale 1	Traveling at relatively high speeds parallel to shore (and the seismic vessel), and then broke off towards shore.	Feeding grounds	143 dB SEL	< 143 dB SEL	6	NA
Gailey et al. (2016)	Whale 2	Changed direction of travel and increased (quadrupled) swim speed (up to 2.7 m/s).	Feeding and traveling at 0.5 m/s	127 dB SEL	NA	NA	Continued swimming offshore until out of sight

Reference	Subjects	Description of Response	Context	RL at Response	Max RL Without a Response	Distance at Response or No Response (km)	Latency to Return to Baseline (after seismic ceased)
Humpback Whales							
McCauley et al. (2000a)	16 Groups (with females)	Avoidance maneuvers before standoff ranges (1.2-4.4 km); startle response at 112 dB rms (n=1). Some individuals approached source at high speeds (4.1 m/s).	Migrating with females	140 dB re 1 µPa	< 112 dB re 1 µPa (rms)	1.3	NA
McCauley et al. (2000a)	2 Groups	Consistent course and speed changes to avoid and maintain a standoff distance from the seismic vessel.	Migrating	157 dB re 1 µPa	NA	4	NA
Malme et al. (1985)	Groups (n=3)	Startle responses at airgun onset on three occasions, but otherwise no avoidance behavior.	Feeding	150 - 169 dB re 1 µPa	172 dB re 1 µP	3.2	NA
Dunlop et al. (2017)	Groups (mother-calf pair)	Small, short-term course deviations of about 500 m. Some whales did not respond, and some responded at lower levels.	Migrating and resting mother-calf pairs	140	NA	< 3	NA
Dunlop et al. (2016)	Groups (n=1-3)	Deviate from predicted heading. However, also decreased swim speeds by 0.4 m/s.	Migrating	111 - 170 dB re 1 µPa^{2}s	NA	0.6 - 13	NA
Dunlop et al. (2015)	32 Groups	Changed dive times and movement (course and speed) but not surface behavior.	Migrating, synchronously surfacing within 100 m of each other	90 - 156 dB re 1 µPa^{2}s	NA	< 10	NA
Blue Whales							

Reference	Subjects	Description of Response	Context	RL at Response	Max RL Without a Response	Distance at Response or No Response (km)	Latency to Return to Baseline (after seismic ceased)
Di Iorio and Clark (2009)	Multiple Individuals (n=17)	Vocal behavior (call rate) significantly increased on seismic days; may have been vocally compensating for the elevated ambient noise levels.	Feeding ground	131 dB re 1 µPa peak to peak (114 dB re 1 µPa SEL)	123	NA	NA
Dunn and Hernandez (2009)	Multiple Individuals (n=8)	No detectable changes in vocal or movement (heading or speed) behavior.	Feeding	NA	145 dB	> 15	NA
Sperm whales							
Madsen et al. (2002)	Adult, Male Individuals	No detectable changes in displacement, avoidance or vocal behavior.	Feeding	NA	146 dB re 1 µPa peak to peak (124 dB re 1 $\mu Pa^2 s$)	> 20	NA
Miller et al. (2009)	Individual adults (n=8)	No change in behavioral state or detectable avoidance behavior, but there were subtle changes in feeding behavior and dives (e.g., significantly less pitching during dives and a non-significant decrease in prey capture).	Feeding, resting; tagged	162 dB re 1 µPa peak to peak (147 dB re 1 µPa rms, 131 dB re 1 $uPa^2 s$ SEL)	NA	1 - 13	NA
Beluga whales							
Miller et al. (2005)	Multiple Groups	Habitat displacement; unexpectedly high sighting rate 20-30 km away from source.	Seasonal shift out of study area	150 - 130 dB re 1 µPa	< 150 dB re 1 µPa	7.8 - 18.3	NA
Harbor porpoises							
Sarnocińska et al. (2020)	Multiple Groups	Vocal activity decreased at sites closest to seismic vessel.	Seasonal presence, feeding	155 dB re 1 $\mu Pa^2 s$	NA	15	After travel 12 km away from source
Ringed, Bearded, and Spotted seals							

Reference	Subjects	Description of Response	Context	RL at Response	Max RL Without a Response	Distance at Response or No Response (km)	Latency to Return to Baseline (after seismic ceased)
Harris et al. (2001)	Multiple individuals (n=387)	Significantly farther away during full-array seismic activities. Most seals would avoid the vessel and either dive or swim away, but they were not displaced much farther than 250 m. No significant response to a single airgun.	Resident species	190 dB re 1 µPa	195 dB re 1 µPa	0.15	After travel 250 m from source

APPENDIX G. DOSE-RESPONSE FUNCTIONS

A suite of candidate Bayesian dose-response models were fitted to the available data, and Bayesian model selection methods were used to indicate the level of support for the different models afforded by the data. The data, models and model fitting methods are described in subsequent sections. Final model selection was undertaken manually, incorporating a suite of factors described below.

G.1. DATA

There were generally two types of data used for this analysis. The first was received levels taken from tagged animals during behavioral response studies on wild animals exposed to an escalating level of sonar. In some of these, an animal was only exposed to a single received level, which was the level input into the model, whereas in others an animal may have been exposed to an escalating received level, for which the level at the time of the response or the maximum level exposed was used in the model.

G.2. CANDIDATE MODELS

Models are first described that apply to individual species (or species groupings); multi-species modelling is then covered. All models share some common features. They are all based on the concept that an individual animal at a particular time (occasion or exposure session) has a dose threshold above which it will show a behavioral response and below which it will not respond. This threshold is denoted t_{ij} where i indicates individual and j indicates exposure session. All models allow for the threshold to vary between individuals and within individuals between occasions. The expected value of the threshold depends on species or species group (see Multi-species models), and in some models it can depend on covariates such as signal type or exposure history. The threshold is assumed to lie between fixed lower and upper bounds, denoted L and U respectively. In other words, no animals respond at a dose at or lower than L (which is typically set at below typical levels of ambient noise), and all animals are assumed to respond at a dose at or higher than U. In the analyses reported here, these bounds were assumed to be $L = 90$ and $U = 200$.

The data are linked to the thresholds in one of three ways. The first way corresponds to cases where animals were observed to respond at a particular dose. These observations are typically associated with a certain level of measurement error, and so the observed dose, y_{ij} was modelled as coming from a normal distribution centered on the threshold:

$$y_{ij} \sim N\left(t_{ij}, \delta^2\right) \qquad (\mathrm{G}-1)$$

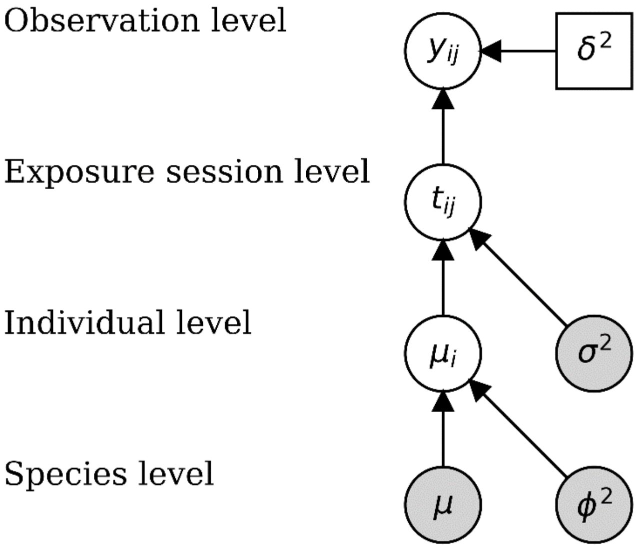
where the tilde symbol “~” means "is distributed according to," $N(x, y^2)$ indicates a normal distribution with mean x and variance y^2, and δ^2 ("delta") is the measurement error variance, which is assumed to be known. In the analyses reported here, we assumed $\delta = 2.5$. The second way corresponds to cases where animals were exposed to an escalating dose, but did not respond at the largest dose administered, $yMax_{ij}$. These data are known as "right censored" - all that is known is that the threshold t_{ij} is between this value and U. The third way corresponds to cases where animals in an escalating dose experiment responded to the first (lowest) dose, $y\mathrm{Min}_{ij}$. These data are "left censored," and all that is known is that the threshold is between L and $yMin_{ij}$.

G.2.1. Monophasic Dose-Response Function

The monophasic dose-response function is based on the model developed and applied to CEE data by Miller et al. (2014) and Antunes et al. (2014). This assumes that the threshold t_{ij} is drawn from a truncated normal distribution with an underlying whale-specific location[1] μ_i ("mu") and within-whale scale σ^2 ("sigma") - this allows for variation over time within whale in its response threshold. The lower and upper truncation bounds are L and U respectively. The whale-specific mean is in turn assumed to come from a truncated normal distribution with location μ and between-whale scale ϕ^2 ("phi") - this allows for variation between whales in their average response threshold. Putting this hierarchy together, the monophasic model is

$$\begin{aligned} y_{ij} &\sim N(t_{ij}, \delta^2) \\ t_{ij} &\sim TN(\mu_i, \sigma^2, L, U) \\ \mu_i &\sim TN(\mu, \phi^2, L, U) \end{aligned} \qquad (\mathrm{G}-2)$$

where $TN(x_i, y^2, L, U)$ denotes a truncated normal distribution with location x, scale y^2, lower bound L and upper bound U. The model structure is illustrated in Figure G-1.



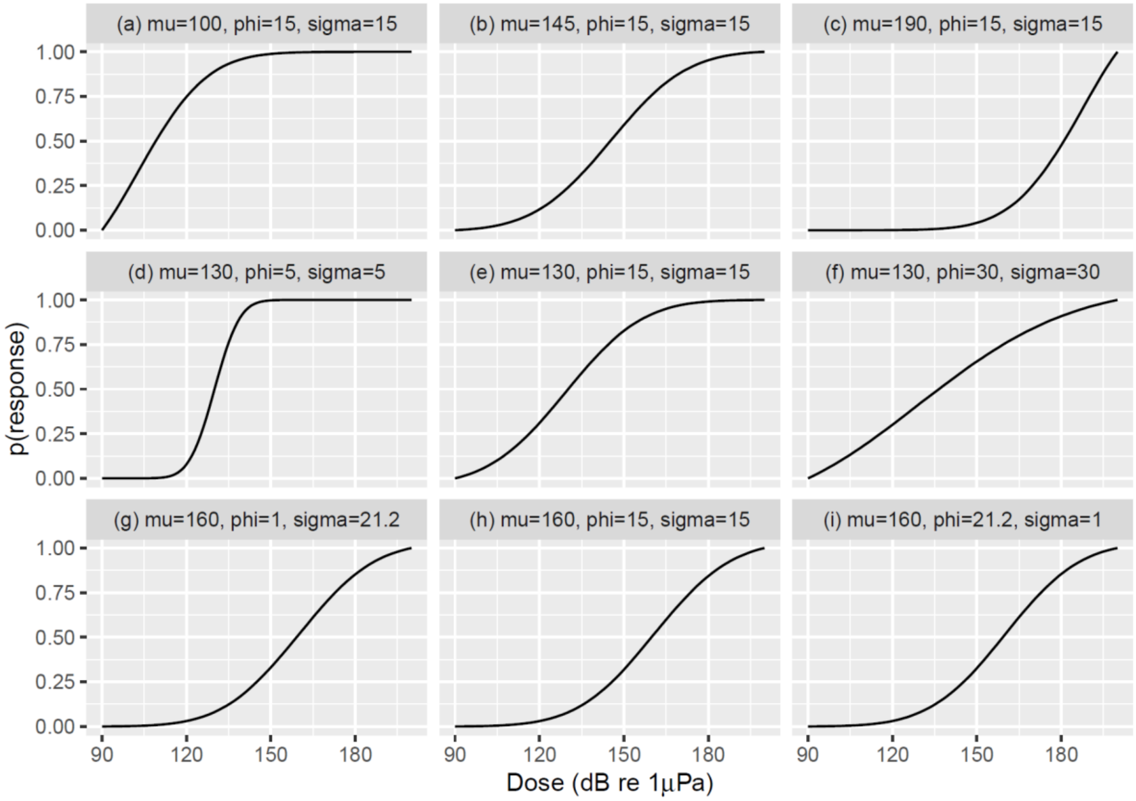
- Variables in the model are denoted by circles, and constants (i.e., known quantities) are denoted by squares.
- Gray shading denotes quantities about which prior distributions are required; the constants required to define these priors are not shown.
- Lines join quantities that are directly related to one another, with arrows showing the direction of inference.
- Symbols are defined in the text.

Figure G-1. Directed acyclic graph of the monophasic dose-response function.

---

[1] The location and scale parameters of a truncated normal distribution are the equivalent of the mean and variance of the (untruncated) normal distribution. The actual mean and variance of a truncated normal distribution is a function of the location, scale, upper bound and lower bound.

Note that, because each threshold is sampled from a truncated normal distribution, the overall population-level dose response function can be thought of (approximately) as coming from a cumulative truncated normal distribution function (CDF), giving the characteristic "S"-shape (with parts of the "S" sometimes truncated) - see Figure G-2 for examples. It is approximate because each trial-within-animal has its own truncated normal CDF set by the animal-level threshold, and the overall function is a mixture of these CDFs.



- In the top row, the value of μ is varied while ϕ and σ are kept constant.
- In the middle row, the value of μ is fixed while ϕ and σ are varied together.
- In the bottom row, the value of μ is fixed while ϕ and σ are varied so as to keep the total between- and within-whale variance ($\phi^2 + \sigma^2$) constant.
- These last three plots show that the population-level dose-response function is nearly identical when within-whale variation is small and between-whale variation large (g) or within-whale variation is large and between-whale variation small (i).

Figure G-2. Examples illustrating a range of possible monophasic dose-response functions.

Prior distributions for model parameters (shown in gray in Figure G-1) were $\mu \sim U(90{,}200), \phi \sim U(0{,}45)$ and $\sigma \sim U(0{,}45)$, where $U(x, y)$ denotes a uniform distribution with lower bound x and upper bound y.

G.2.2. Covariates in the Monophasic Dose-Response Function

The monophasic model with covariates was also developed by Miller et al. (2014) and Antunes et al. (2014). In their models, the covariates were signal type (LFAS vs MFAS) and exposure history (previously exposed to sonar during the experiment or not). They used Bayesian model selection methods, based on computing posterior model probabilities, to determine which covariates were supported by the data.

The current model extends this by allowing up to four covariates: signal type (e.g., LFAS vs MFAS), exposure history (first or subsequent), behavior state (feeding or not feeding), and range to closest source (in km, a numerical covariate). Again, Bayesian model selection methods will be used to determine which are supported by the data. In theory the model could be adapted to accommodate more covariates, but these four are the only ones for which data were available in all cases used in this analysis. If we denote the vector of covariate values as $\boldsymbol{z}_{ij}$ then the monophasic covariate model is

$$
\begin{aligned}
y_{ij} &\sim N\left(t_{ij}, \delta^2\right) \\
t_{ij} &\sim TN\left(\mu_{ij}, \sigma^2,\ L,\ U\right) \\
\mu_{ij} &= \mu_i + \beta z_{ij} \\
\mu_i &\sim TN(\mu, \phi^2,\ L,\ U)
\end{aligned}
\qquad (\mathrm{G}-3)
$$

where β is a vector of parameters determining the effect of the covariates on the threshold. The model structure is illustrated in Figure G-3.

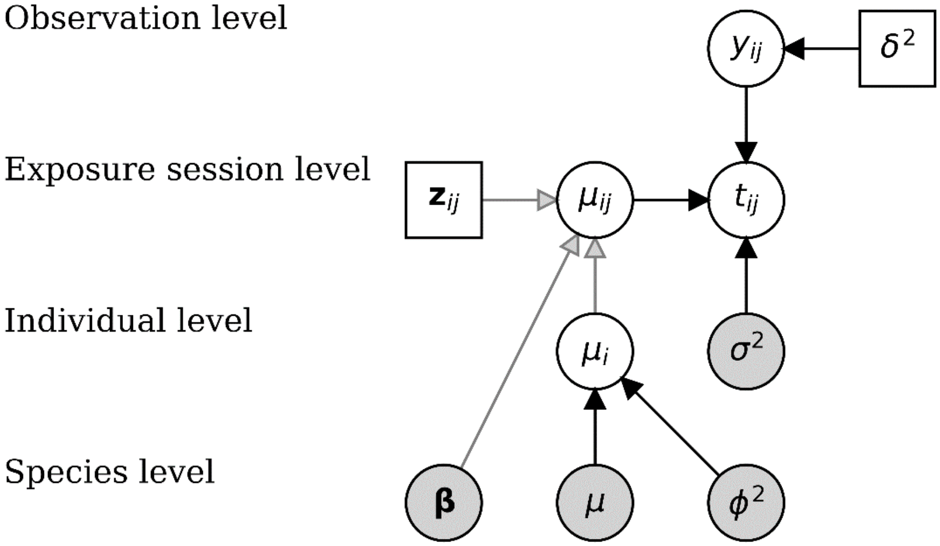


Figure G-3. Directed acyclic graph of the monophasic dose-response function with covariates.

In addition to the notation defined in the legend for Figure G-1, black lines show stochastic relationships and grey lines deterministic ones (μ_{ij} is a deterministic function of μ_i, β, and $\mathrm{z_{ij}}$ – see Equation G-3).

The prior distributions for each element of β was $N(0, 30)$.

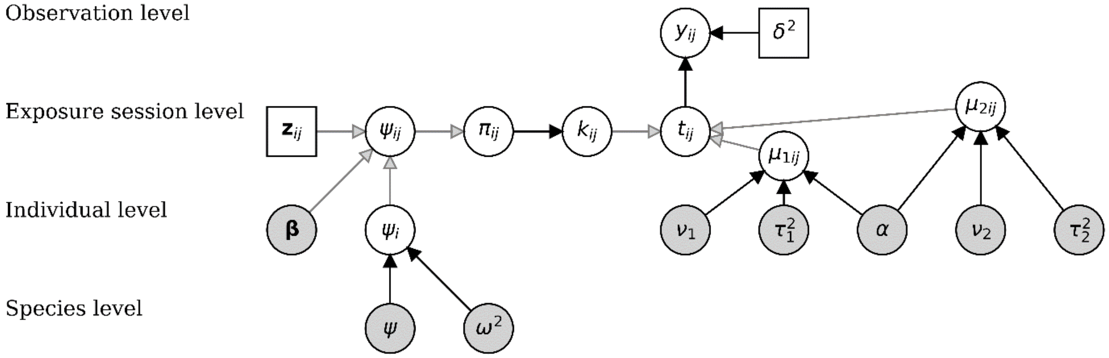
G.2.3 Biphasic Dose-Response Function

This model, which is a generalization of the monophasic functions described above, was developed and used in Department of the Navy (2017) (although the model used in that report did not include the use of covariates). It is based on the conceptual model for dose-response of Ellison et al. (2011). These authors hypothesized that the dose-response function is made up of two components - a context dependent component that operates at lower doses and a dose-dependent component (although note that both distributions are, in fact dose-dependent to some extent) that could be thought to be driven by uncomfortable loudness, or perhaps annoyance. The lower component is called context-dependent because the probability of an individual animal displaying a context-dependent response depends upon contextual variables such as its behavior, previous exposure, etc. This was implemented in Department of the Navy (2017) by allowing the threshold t_{ij} to come from one of two truncated normal distributions, one (the context-dependent distribution) with lower exposure values than the other (the dose-dependent distribution). One may expect the standard deviation of the context-dependent function to be larger than the dose-response function, leading to a "flatter" CDF, and also to have the probability for each animal and trial of the threshold being sampled from the lower function being dependent on the context-related covariates (Figure G-4).

The biphasic model can be written as follows:

$$
\begin{gathered}
y_{ij} \sim N\left(t_{ij}, \delta^2\right) \\
t_{ij} = k_{ij}\mu_{1ij} + \left(1 - k_{ij}\right)\mu_{2ij} \\
\mu_{1ij} \sim TN(\nu_1, \tau_1^2,\ L,\ \alpha) \\
\mu_{2ij} \sim TN(\nu_2, \tau_2^2,\ \alpha,\ U) \\
k_{ij} \sim Bern\left(\pi_{ij}\right) \\
\pi_{ij} = \Phi\left(\psi_{ij}\right) \\
\psi_{ij} = \psi_i + z_{ij}\beta \\
\psi_i \sim N(\psi, \omega^2)
\end{gathered}
\tag{G-4}
$$

where μ_{1ij} and μ_{2ij} are the thresholds from the context-dependent and dose-dependent distributions respectively. Both follow truncated normal distributions with location and scale parameters v_1 ("nu"), τ_1^2 ("tau") and v_2, τ_2^2 respectively. The upper bound on the context-dependent threshold is α ("alpha"), and this forms the lower bound of the dose-dependent threshold. The threshold actually displayed by the animal, t_{ij}, is determined by an "indicator variable," k_{ij} which takes the value 1 when the animal displays the context-dependent threshold and 0 when it displays the dose-response threshold. k_{ij} follows a Bernoulli distribution (denoted Bern in equation [G-4]) with probability of taking the value 1 determined by the variable π_{ij}. This probability is linked to covariates z_{ij} and an intercept parameter ψ_i ("psi") via a probit link: $\Phi(x)$ in equation (G-4) denotes a normal cumulative density function evaluated at x. The intercept ψ_i follows a normal distribution with mean ψ and variance ω^2 ("omega"). The model structure is illustrated in Figure G-4.



Notation is defined in the legends for Figure G-1 and Figure G-2.

Figure G-4. Directed acyclic graph of the monophasic dose-response function with covariates.

Some examples (without covariates) are shown in Figure G-5. These (partly) illustrate the range of dose-response functions available. Some combinations of parameters produce functions that are very similar to those from the monophasic function (compare, e.g., Figure G-5 part C and Figure G-2 part C). Given the biphasic models have 7 parameters compared to 3 for monophasic, in a model selection situation where the candidate set includes both mono- and bi-phasic models, it is likely that the biphasic models will only be chosen if the estimated shape is substantially different from a monophasic (e.g., Figure G-5 part a, d, e, g, and j).

Parameter priors were chosen to constrain the parameters within reasonable ranges. For example, ψ could potentially take any value on the real line, but values far from 0 are not realistic - when ψ is -2 the expected proportion of the population in the context-dependent phase is 0.02, while when ψ is 2 the expected proportion in the context-dependent phase is 0.98 (these figures assume $\omega = 0$, but similar values are obtained with other reasonable values of ω). With proportions this low or high, the dose response function is effectively monophasic. Hence the prior chosen for ψ was $\mathrm{N}(0,1)$. With similar motivations, priors on the other parameters were $\nu_1 \sim U(90, 1\ 30)$, $\nu_2 \sim U(130, 200)$, $\alpha \sim U(110, 160)$, $\tau_1 \sim U(0, 45)$, $\tau_2 \sim U(0, 45)$, $\beta \sim N(0, 30)$.

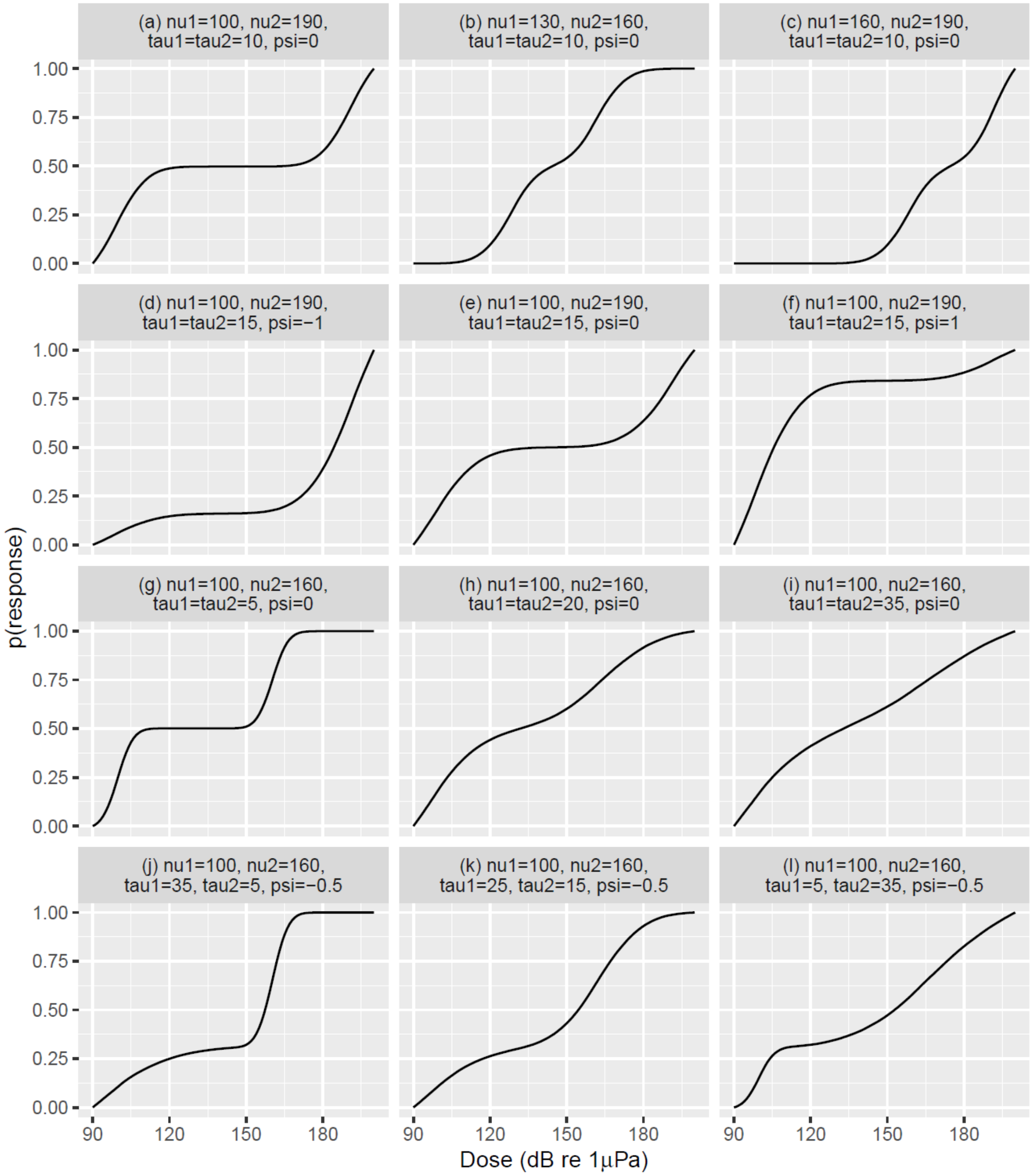


Figure G-5. Examples illustrating a range of possible biphasic dose-response functions.

In the top row, the values of υ_1 and υ_2 are varied, in the second row ψ is varied, in the third row τ_1 and τ_2 are varied but kept equal while on the bottom row τ_1 and τ_2 are varied independently. In all cases, ω is fixed at 0 since it has almost no effect on the population-level dose response function. The functions are averaged over values of α uniformly distributed between υ_1 and υ_2.

G.3. MULTI-SPECIES MODELS

In a multi-species model, species are grouped together into one or more species group(s). Each group is then assigned its own mean (or location) parameter. In the case of the monophasic functions, this means each species group has its own μ. For the biphasic model, each species group has its own v_1, v_2, and α. Note that all species are (currently) assumed to share the same variance (or scale) parameters this is a strong assumption that should be examined in future. Note also that the effect of covariates, if in the model, are assumed to be the same on all species. More complex covariate models could be envisaged, but it was considered that the data were not sufficient to support the number of parameters that would be required.

G.4. MODEL FITTING, AUTOMATED MODEL SELECTION, AND MODEL AVERAGING

The above models were fitted to the data using a Reversible Jump Markov chain Monte Carlo (RJMCMC) algorithm implemented in the statistical software R, version 4.1.2 (R Core Team 2021). The algorithm, with associated utilities for summarizing and plotting results, and for model diagnostics, is freely available as an R package, espresso (Bouchet et al. 2021). The current version is 1.6.1. The package comes with a code vignette illustrating its use.

The RJMCMC algorithm probabilistically moved between different models with probability proportional to their posterior model probability; within model parameter values were sampled according to their posterior model probabilities. This allows quantification of the support for each model, for parameter estimation within model and, importantly, for estimation of the population-level dose-response curve accounting for both model and parameter uncertainty. The models explored included potential species groupings and inclusion of each potential covariate: signal type, exposure history, behavior state and range. Model selection for a monophasic vs biphasic curve was not available, so the type of curve had to be pre-selected. Note that different model types were applied to all species groupings - for example: if a covariate was included then it was included for all species groupings; if a biphasic model was being used, then biphasic models were used for all species groupings. With more data it may be possible to explore models where covariates or bivariate functions apply only to some species groupings.

Convergence diagnostics and other post-processing was implemented in the software R. Convergence was assessed by examining trace plots and the BGR statistic (Brooks & Gelman, 1998) for each parameter, using three MCMC chains run from random start points for 2,000,000 iterations. We determined convergence was achieved after <1,000,000 iterations in all cases, and so inference was based on a burn-in of 10,000 iterations followed by 200,000 samples per chain and thinned by a factor of 10. The resulting Monte Carlo error in estimates was negligible.

Estimates were quantified as posterior means, and 95 percent credible intervals obtained as the 2.5th and 97.5th quantiles from the posterior distribution.

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