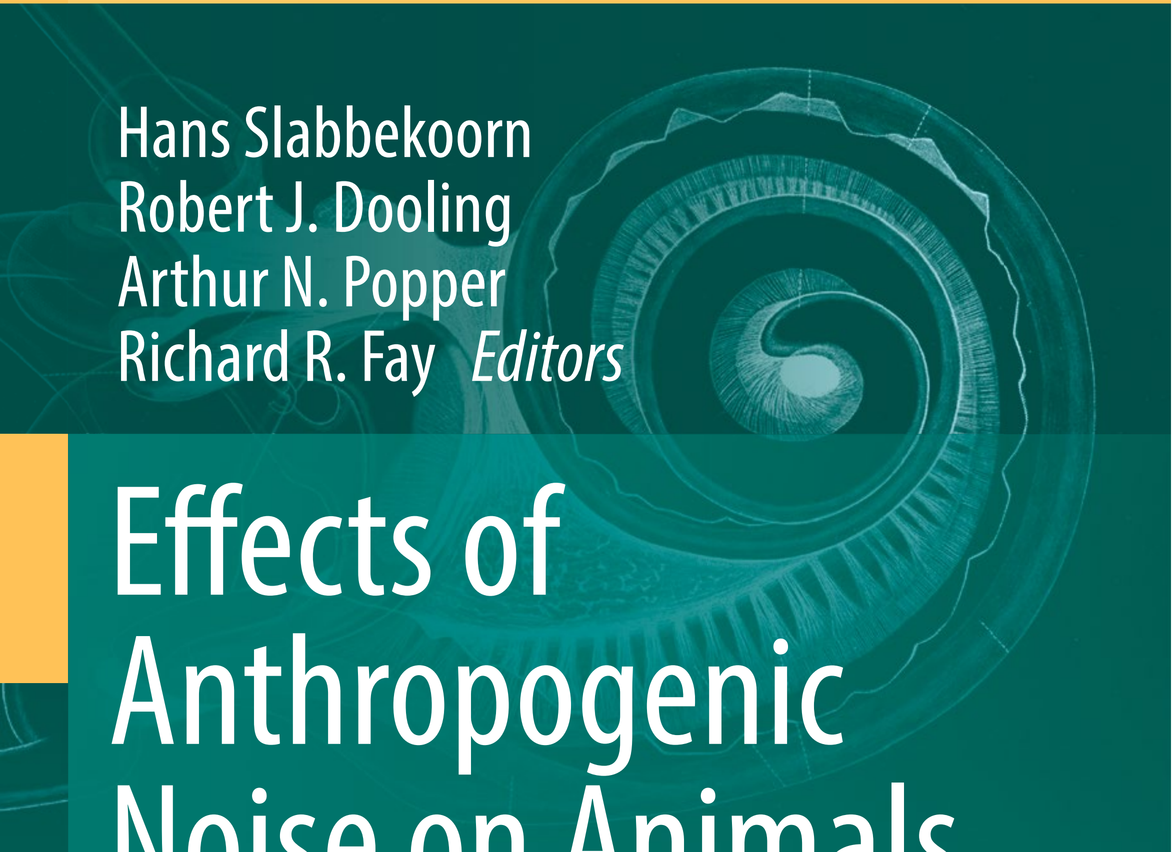
Springer Handbook of Auditory Research



Hans Slabbekoorn
Robert J. Dooling
Arthur N. Popper
Richard R. Fay *Editors*

Effects of Anthropogenic Noise on Animals

ASA Press

Springer

Hans Slabbekoorn • Robert J. Dooling
Arthur N. Popper • Richard R. Fay
Editors

Effects of Anthropogenic Noise on Animals

ASA Press

Springer

Editors
Hans Slabbekoorn
Faculty of Science
Institute of Biology Leiden (IBL)
Leiden University
Leiden, The Netherlands

Arthur N. Popper
Department of Biology
University of Maryland
Silver Spring, MD, USA

Robert J. Dooling
Department of Psychology
University of Maryland
College Park, MD, USA

Richard R. Fay
Loyola University Chicago
Chicago, IL, USA

ISSN 0947-2657 ISSN 2197-1897 (electronic)
Springer Handbook of Auditory Research
ISBN 978-1-4939-8572-2 ISBN 978-1-4939-8574-6 (eBook)
https://doi.org/10.1007/978-1-4939-8574-6

Library of Congress Control Number: 2018953164

© Springer Science+Business Media, LLC, part of Springer Nature 2018
This work is subject to copyright. All rights are reserved by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed.
The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.
The publisher, the authors and the editors are safe to assume that the advice and information in this book are believed to be true and accurate at the date of publication. Neither the publisher nor the authors or the editors give a warranty, express or implied, with respect to the material contained herein or for any errors or omissions that may have been made. The publisher remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Printed on acid-free paper

This Springer imprint is published by the registered company Springer Science+Business Media, LLC part of Springer Nature.
The registered company address is: 233 Spring Street, New York, NY 10013, U.S.A.

Contents

Chapter 10
Effects of Noise on Marine Mammals

Christine Erbe, Rebecca Dunlop, and Sarah Dolman

Abstract Marine mammals (whales, dolphins, seals, sea lions, sea cows) use sound both actively and passively to communicate and sense their environment, covering frequencies from a few hertz to greater than 100 kHz, differing with species. Although a few documents on marine mammal sound production and reception date back 200 years, concern about the effects of man-made noise on marine mammals has only been documented since the 1970s. Underwater noise can interfere with key life functions of marine mammals (e.g., foraging, mating, nursing, resting, migrating) by impairing hearing sensitivity, masking acoustic signals, eliciting behavioral responses, or causing physiological stress. Many countries are developing and updating guidelines and regulations for underwater noise management in relation to marine mammal conservation. In the United States, the Marine Mammal Protection Act, enacted in 1972, is increasingly being applied to underwater noise emission. Common mitigation methods include (1) time/area closures, (2) the establishment of safety zones that are monitored by visual observers or passive acoustics and that lead to shut-down or low-power operations if animals enter these zones, (3) noise reduction gear like bubble curtains around pile driving, and (4) noise source modifications or operational parameters like soft starts. Mitigation management mostly deals with single operations (like a one-month seismic survey). Key questions that remain are how noise impacts accumulate over time and multiple exposures, how multiple acoustic and nonacoustic stressors interact, and how effects on individuals affect a population as a whole.

C. Erbe (✉)
Centre for Marine Science and Technology, Curtin University, Perth, WA, Australia
e-mail: c.erbe@curtin.edu.au

R. Dunlop
Cetacean Ecology and Acoustics Laboratory, School of Veterinary Science,
University of Queensland, Gatton, QLD, Australia
e-mail: r.dunlop@uq.edu.au

S. Dolman
Whale and Dolphin Conservation, Chippenham, Wiltshire, UK
e-mail: sarah.dolman@whales.org

H. Slabbekoorn et al. (eds.), *Effects of Anthropogenic Noise on Animals*,
Springer Handbook of Auditory Research 66,
https://doi.org/10.1007/978-1-4939-8574-6_10

Keywords Behavioral response · Bioacoustic impact · Environmental management · Marine Mammal Protection Act · Marine mammals · Masking · Population consequences of acoustic disturbance · Population consequences of disturbance · Safety zone · Stress · Temporary threshold shift · Underwater noise

10.1 Introduction

There are about 130 species of marine mammals taxonomically grouped into 21 families (Table 10.1). Cetaceans (whales, dolphins, and porpoises) and sirenians (sea cows) are fully aquatic. The marine carnivores (seals, sea lions, and otters), however, split their time between land and water. Marine mammals inhabit all of the world's oceans, from the deep offshore waters (with sperm whales [*Physeter macrocephalus*], elephant seals [*Mirounga* sp.], and Cuvier's beaked whales [*Ziphius*

Table 10.1 Marine mammal taxonomy

Latin name	Common name
Order Cetacea	Whales, dolphins & porpoises
Suborder Mysticeti	Baleen whales
Family Balaenidae	Right and bowhead whales
Family Neobalaenidae	Pygmy right whale
Family Balaenopteridae	Rorquals
Family Eschrichtiidae	Gray whale
Suborder Odontoceti	Toothed whales
Family Delphinidae	Oceanic dolphins
Family Platanistidae	South Asian river dolphins
Family Iniidae	Amazon river dolphin, boto
Family Lipotidae	Chinese river dolphin, baiji
Family Pontoporiidae	Franciscana
Family Phocoenidae	Porpoises
Family Monodontidae	Narwhal and beluga
Family Physeteridae	Sperm whale
Family Kogiidae	Pygmy and dwarf sperm whales
Family Ziphiidae	Beaked whales
Order Sirenia	Sea cows
Family Trichechidae	Manatees
Family Dugongidae	Dugongs
Order Carnivora	Carnivores
Family Mustelidae	Marine otters
Family Ursidae	Polar bear
Suborder Pinnipedia	Seals, sea lions, and walrus
Family Phocidae	True seals
Family Otariidae	Eared seals and sea lions
Family Odobenidae	Walrus

cavirostris] diving down to 2–3 km; e.g., Schorr et al. 2014) to the shallow coastal waters, and a few species, such as river dolphins, are in rivers.

Marine mammals live in a medium through which sound propagates better than potential cues or signals of any other sensory modality, such as light. They have therefore evolved to use sound both actively and passively in all biologically important behaviors (Tyack 2000), including socializing, traveling, hunting, breeding, and parental care. Examples of marine mammal sounds are the behavior-specific and signature whistles of dolphins (Caldwell and Caldwell 1965; Herzing 1996) and the song of humpback whales (*Megaptera novaeangliae*; Payne and McVay 1971). Cultural transmission of sound structure is evident in killer whales (*Orcinus orca*; Ford 1991) who have dialects that can be used to distinguish between populations living in the same area. Odontocetes (toothed whales) also emit sound to echolocate during navigation and foraging (Au 1993). Examples of passive sound usage include listening to acoustic cues from the environment, predators, and prey (e.g., Deecke et al. 2002; Gannon et al. 2005).

Knowledge of the auditory capabilities of marine mammals is important to understand their acoustic ecology, how they sense their environment, over what ranges they remain in acoustic contact, whether they can detect predators and prey, and how they receive ambient and man-made noise. Studies examining the hearing of marine mammals date back two centuries (e.g., Home 1812). However, it was not until the 1970s that underwater sound emitted by human activities in the oceans was first recognized to sometimes be in conflict with marine mammals. Payne and Webb (1971) concluded that ship noise decreased the communication range of baleen whales, a concern still echoing 40 years later (Clark et al. 2009). Impacts documented in the 1970s also include hauled-out walrus (*Odobenus rosmarus*) disturbance by aircraft associated with Arctic petroleum exploration (Salter 1979) and, opportunistically, a beaked whale mass stranding coincident with naval maneuvers (van Bree and Kristensen 1974). The Marine Mammal Protection Act (MMPA; passed in 1972) and the Endangered Species Act (ESA; passed in 1973) set the legal framework for conservation (including marine mammals) in the United States. A symposium on the effects of sound on wildlife held in Spain in 1977 included discussions of the impacts of man-made sound on marine biological systems and resulted in a book on the effects of man-made noise on wildlife (Fletcher and Busnel 1978).

Since then, dedicated research rather than opportunistic observations has grown (Williams et al. 2015), leading to the landmark book *Marine Mammals and Noise* (Richardson et al. 1995). In the 1990s, the Heard Island Feasibility Test and the Acoustic Thermometry of Ocean Climate (ATOC) experiments caused widespread public concern, which resulted in a large-scale marine mammal research program (National Research Council 1994, 2000). Much of the research on the sound impacts on marine mammals over the past two decades has been driven by "take" authorizations under the MMPA[1] that require baseline and in situ monitoring. In fact, the MMPA has increasingly been applied to sound sources so that nearly all "incidental

---

[1] The MMPA defines "take" as "hunt, harass, capture, or kill."

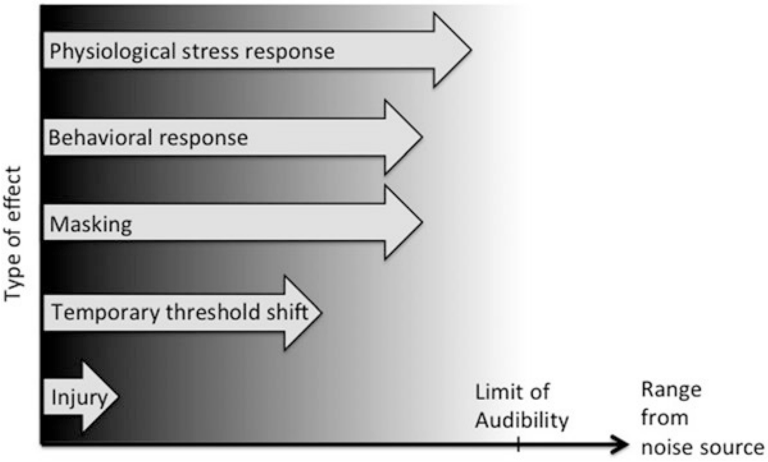


Fig. 10.1 Assuming a source of sound is located on the left side, its received level decreases with range. Near the source, a variety of bioacoustic impacts may be possible. Some effects such as stress, behavioral responses, or masking of communication may extend to long ranges where the sound is just audible. The ranges over which the above effects happen and the order of effects by range may depend on the type of sound, its spectral and temporal characteristics, the local sound propagation environment, ambient-noise conditions, the characteristics of the auditory system of the receiving animal, its current behavioral state, and/or past experience

take" authorizations issued under the Act today are at least partly, and in many cases primarily, focused on acoustic impacts (Roman et al. 2013). Public concern in the United States has culminated in law suits under the MMPA and ESA, specifically criticizing the US Navy's use of active sonar (Zirbel et al. 2011).

Underwater sound from human activities can have a variety of immediate effects on marine mammals, including injury, temporary loss of hearing, behavioral responses, masking, and stress (Fig. 10.1). Severity of the impacts typically decreases with the range from the sound source and depends on the specific scenario consisting of the type of sound, the acoustic environment, and the receiving individual. At the longest ranges, the sound might barely be audible or discernible above the ambient noise. The animal's hearing abilities and the level of ambient noise determine the range of audibility.

In extreme cases, close to the source, injuries such as tissue or organ damage (e.g., a permanent loss of hearing called permanent threshold shift [PTS]; see Southall et al. 2007) may be found (see Saunders and Dooling, Chap. 4). If hearing loss recovers with time, it is termed a temporary threshold shift (TTS). TTS has been demonstrated in a number of odontocetes and pinnipeds (walruses, seals, and sea lions) in controlled sound exposure experiments (e.g., Kastelein et al. 2013). Severe to profound hearing loss has been measured in some wild, stranded odontocetes (Mann et al. 2010), but the cause and whether this was TTS or PTS is unknown. Less extreme behavioral responses might be seen both near and far from the source. Beluga whales (*Delphinapterus leucas*), for example, responded to faraway (tens of kilometers) icebreakers that were expected to be barely audible (Finley et al. 1990). Acoustic masking occurs when noise interferes with the detection of acoustic signals important to animals. This can also happen at long ranges, such as when the call of a faraway conspecific is masked by similarly faint man-made noise. Such "extreme" scenarios were modeled for icebreakers and beluga whales based on behavioral masked hearing experiments with a captive beluga whale involving beluga calls and different types of icebreaker sound at different levels (Erbe and Farmer 1998, 2000). Stress is a physiological response and might be a direct result of exposure to man-made sounds that are unknown or resemble the sounds of predators or are an indirect result of exposure when injury or masking cause stress (Wright et al. 2007). Therefore, stress can occur at various ranges. The concept of impact ranges or zones, as illustrated in Fig. 10.1, applies to the immediate impacts on individual animals near an active source, and most evidence of sound impacts on marine mammals is related to short-term, individual responses. Figure 10.1 does not capture extreme responses like mass strandings (Cox et al. 2006), where whales were likely subjected to only moderate received levels not expected to cause physical damage and yet stranded and died due to perhaps more complex processes.

The National Research Council (2005) defined an effect as "biologically significant" if it keeps an animal from growing, surviving, and reproducing, thereby potentially affecting the survival of its population. The challenge is to figure out how temporary responses accumulate over space, time, and individuals to ultimately lead to population-level effects. Behavioral effects might accumulate over many years before such impacts are realized. However, in the case of sound-related mass strandings, a single instance of behavioral disturbance can affect the local population. A framework to develop the progression from immediate, individual impacts to population impacts is provided by the population consequences of disturbance (PCoD) model, and this chapter is organized along the stages of the PCoD model.

10.2 Underwater Sound

In this chapter, the focus is on waterborne sound. Pinnipeds, polar bears (*Ursus maritimus*), and otters (*Lutrinae*) spend time both on land and in water and are hence subject to sound impacts in both media. Responses to airborne sound are not reviewed here. Instead, the reader is referred to the comprehensive review work by Richardson et al. (1995).

Understanding the ambient sound conditions in marine mammal habitats is important because ambient sound limits the detection of and likely response to man-made sound (see Larsen and Radford, Chap. 5). The ocean is naturally noisy. Wind, rain, breaking waves, cracking polar ice, and subsea earthquakes and volcanoes all contribute to the ambient noise in certain geographic regions. Some of these natural sounds propagate over hundreds to thousands of kilometers so that Antarctic ice breakup is recorded on hydrophones near Australia (Gavrilov and Li 2007). Wenz (1962) summarized the spectral characteristics of typical ambient-noise sources,

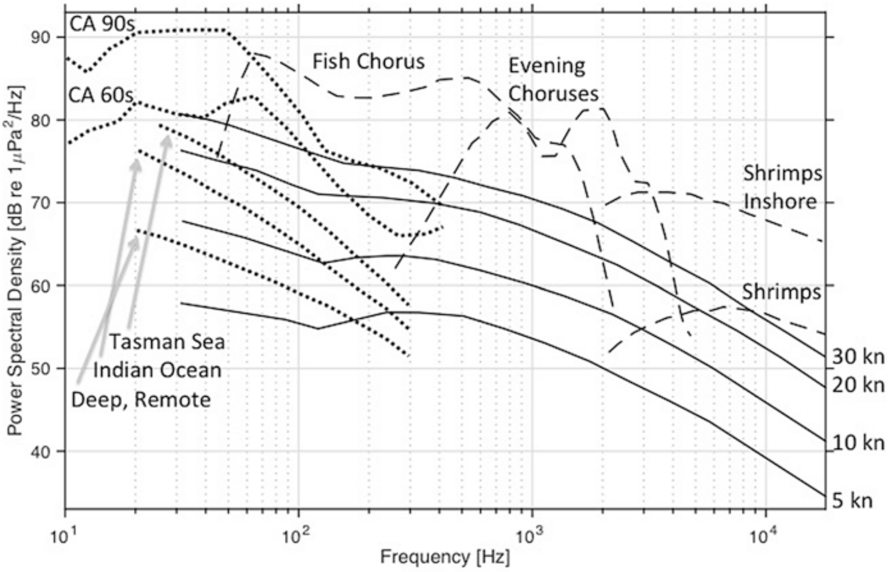


Fig. 10.2 Typical source spectra of ambient noise: wind, biological choruses, and distant shipping. Distant shipping sound was recorded at five locations: off California in the late 1990s (CA 90s; Andrew et al. 2002) and early 1960s (CA 60s; Wenz 1969); in the Tasman Sea, Australia; in the southeast Indian Ocean; and in Australian deep water remote from shipping lanes. Wind-dependent noise is shown at four different wind speeds. The tropical biological choruses vary with location, time of day, and season (Cato 1978). Shrimp noise typically only exists in shallow (<40 m) water. Based on Cato (2008)

yielding the widely used *Wenz curves*. Other significant contributors to underwater sound are, of course, marine animals, including mammals, fishes, crustaceans, and urchins, many of which create biological choruses (Cato 1978). Under conditions where many animals call at the same time, they can raise the ambient level in a characteristic frequency band for several hours. Typical spectra of such choruses along with wind-dependent ambient noise and distant shipping are shown in Fig. 10.2.

All marine operations produce underwater sound: shipping, transport, oil and gas, defense, tourism, fishing, offshore minerals, offshore wind and water energy, and on- and near-shore construction (Richardson et al. 1995; Wyatt 2008). Sound produced in air, such as by airplanes and helicopters, transmits into the water at incidence angles less than 13° from the vertical. Similarly, sound produced in air on ship decks or oil platforms enters the water by radiation through the hull or support legs. Figure 10.3 shows smoothed and simplified example source spectra of underwater noise emitted by human activities. Such source spectra are typically used in conjunction with sound propagation models (e.g., Jensen et al. 2011) to predict received levels at some range for the purpose of environmental impact assessment.

The nature of the sound propagation environment plays an important role because it changes the spectral and temporal characteristics of a sound as it travels from the

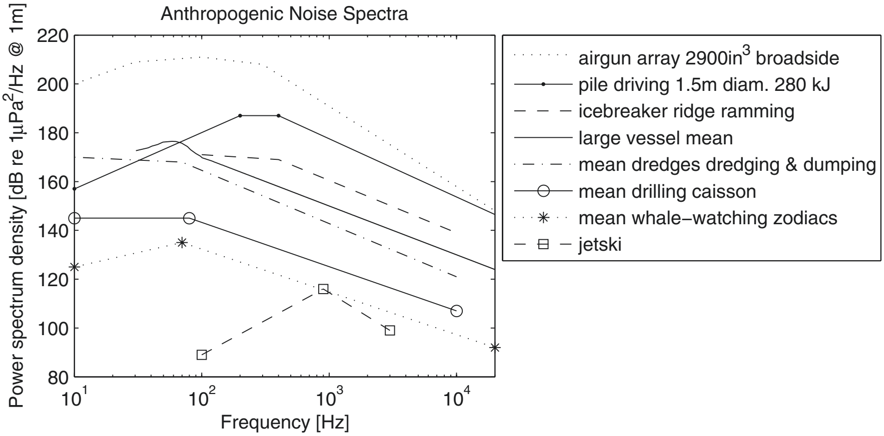


Fig. 10.3 Stylized far-field equivalent source spectra of example anthropogenic operations (reprinted from Erbe 2012). All sounds were recorded at some range and back-propagated to a nominal distance of 1 m. In the case of the pulsed sources (airgun array and pile driving), the power spectrum density was computed over the 90% pulse length, which is the duration from the 5% to the 95% point on the cumulative energy curve (see, e.g., Erbe 2011)

source to the receiver (see Larsen and Radford, Chap. 5), in this case, a marine mammal. Hence, propagation affects the potential for bioacoustic impact. Overall, the broadband received sound level attenuates with range, but the rate of attenuation depends on the bathymetry, the hydroacoustic profile of the water column, and the geoacoustic parameters of the upper seafloor. The spectral characteristics change with range because energy at different frequencies is attenuated at different rates. In deep water, energy at low frequencies (<100 Hz) can travel over very long ranges, which is why ship noise has the potential to mask the calls of baleen whales over many tens of kilometers. In the case of pulsed sound, the duration of the pulse typically increases with range. Thus, sound from a seismic airgun array might consist of 100-ms pulses every few seconds and marine mammals close to the source likely detect the calls of conspecifics through the quiet gaps in the seismic sound pattern. At a 100-km range, however, each pulse might be several seconds long (Guerra et al. 2011), forming a continuous (albeit band-limited) sound.

As the waveform of the sound changes during propagation, the various acoustic quantities, which might be responsible for different types of effects in different animal species, also change. Obviously, source level alone is no indicator for impact. The received root-mean-square sound pressure level (SPL_{rms}), the received sound exposure level (SEL; weighted or not), and the received peak SPL (SPL_{peak}) have most commonly been investigated as potential indicators for impact (e.g., Southall et al. 2007). Other parameters might play a role, e.g., the signal-to-noise ratio, kurtosis, duty cycle, and/or pulse rise time. Different acoustic quantities, either alone or in combination, are likely linked to different types of effect, and this link might be different in different species. Comparing sound sources merely by source level or source spectrum is inappropriate. As such, Fig. 10.3 should not be used to rank the likelihood of impact of different types of sound.

10.3 Responses to Sound

10.3.1 Responses to Natural Sound

Marine mammals have evolved in a world that is filled with natural sound. Wind-dependent elevation of ambient noise is ubiquitous and overlaps in frequency with many marine mammal communication sounds. How do marine mammals cope with this?

The changes in human speech in response to elevated ambient noise are collectively known as the Lombard effect, where signalers modify vocal characteristics such as level, pitch, and/or rate of signal production in a noisy environment by which they may improve signal detection probability at the receiver (Lombard 1911). Humpback whales were found to increase the source level of their social vocalizations by 0.9 dB for every 1-dB increase in wind-elevated ambient noise (Dunlop et al. 2014), maintaining about 60-dB signal excess above the ambient-noise level in medium wind conditions. There was evidence, however, of an upward limit to this response, perhaps due to anatomical constraints. When the ceiling is reached, a change in spectral characteristics or call type might be an alternative option by which to communicate in noisy conditions. Another study found that humpback whales switched communication signal type from primarily vocal signals to mechanical signals generated at the surface (breaches, slaps) in the same spread of ambient-noise levels as in the Lombard study (Dunlop et al. 2010). It is unclear whether the use of different signal types changed the message sent or maintained the original communication.

Vocalizing conspecifics, such as singing humpback whales, also raise the background noise in which animals must continue to communicate with one another. The "cocktail party effect" (Cherry 1953) is experienced by receivers due to acoustic interference from multiple vocalizing conspecifics (akin to the challenge humans face when communicating with each other at a noisy party). To some extent, the receiver is able to focus on the signaler and filter out the background noise of conspecific sounds. Most of the research on how animals communicate in noisy social aggregations has been carried out in birds and frogs (see Bee and Micheyl 2008 for a review; see also Simmons and Narins, Chap. 7). Many marine mammals live in large groups too, making a cacophony of calls. How one group member is able to communicate successfully with another in among the chatter has not been studied.

Currently, there is no information in the literature on behavioral changes (e.g., in diving behavior or movement patterns) or physiological changes (e.g., TTS or stress) in response to natural fluctuations in ambient noise. Understanding the

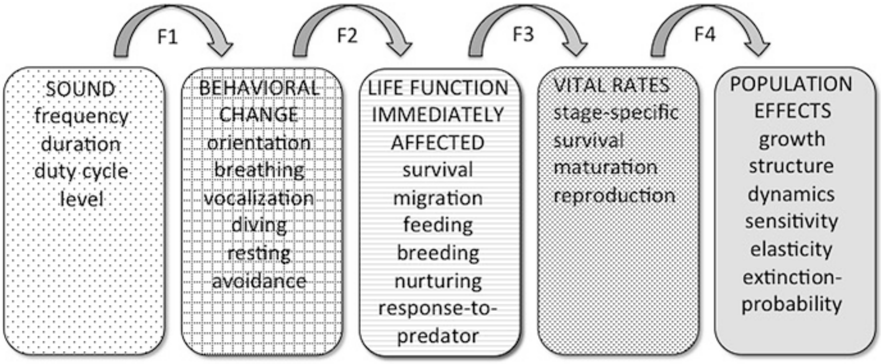


Fig. 10.4 Population consequences of acoustic disturbance (PCAD) model breaking down the link between sound and population-level impact into a set of stages connected by transfer functions (F1-F4). Modified from the National Research Council (2005)

natural repertoire of responses and their frequency of occurrence might aid in assessing the biological significance of responses to man-made noise.

10.3.2 The Population Consequences of Disturbance Framework

The biggest challenge in bioacoustic impact assessments and in the management of underwater sound is how to progress from short-term observations of individual responses to predictions of population-level consequences. The population consequences of acoustic disturbance (PCAD) model (National Research Council 2005) was developed as a conceptual framework linking behavioral and some physiological responses to man-made sound with biologically significant, population-level effects (Fig. 10.4). The PCAD model breaks the causal relationship between individual behavior change and population effects into a set of more manageable stages connected by transfer functions. The model starts with measurements of sound characteristics, such as the spectral characteristics and the duration, and links these via transfer function 1 to short-term, individual behavior change, such as a change in dive pattern or vocalization rate. A sudden change in diving might affect an animal's foraging activity. An onset of avoidance might disrupt resting or nursing. Disruption of vocalization might interfere with breeding. Transfer function 2 makes these links between behavioral change and the life functions immediately affected. If feeding is repeatedly disrupted, an animal might suffer caloric and nutritional deficiencies affecting its survival. Interrupted breeding comes at a cost to reproduction. Transfer function 3 links life functions to vital rates. Transfer function 4 yields population effects, such as a reduced population growth rate and changes in population structure. Unfortunately, the paucity of data underlying the various stages and

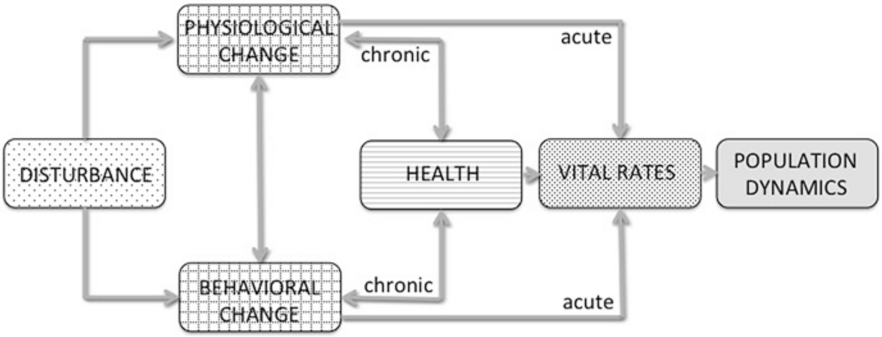


Fig. 10.5 Population consequences of disturbance (PCoD) model linking disturbance of individuals to population-level effects (Harwood et al. 2014)

transfer functions limits the PCAD model to a conceptual rather than predictive model.

The PCAD framework was broadened to include disturbance other than man-made noise and to account for the impact of disturbance on physiology in addition to behavior (Harwood et al. 2014; New et al. 2014). The result is the PCoD model (Fig. 10.5). PCoD begins with a disturbance (either acoustic or not), which results in a behavioral or physiological response. In the acute case, these responses immediately affect vital rates (e.g., survival or reproduction). For chronic disturbance, the animal's health is impaired, eventually impacting vital rates. Changes in vital rates lead to changes in population dynamics.

The PCoD model has been translated into a formal, mathematical model that can be parameterized with data from case studies. The data needed to implement the PCoD model for the case of acoustic disturbance include the sound field around the source, the sound parameters and their levels that cause behavioral or physiological responses (ideally as dose-response curves), the number of animals that are likely going to be exposed to these levels, the relationship between physiological impacts and vital rates (ideally by age and gender), the relationship between the number of behavioral disturbances and vital rates, the population size, and demographic parameters. Uncertainty in all of these input parameters can be included in the model (Harwood et al. 2014).

10.3.3 Disturbance

Disturbance in the PCoD model can be any interruption of "normal" functioning and leads to behavioral or physiological changes in an animal. The disturbance might be some form of alteration of the environment such as climate change, artificial light at nighttime, chemical discharge, the mere presence of an oilrig or vessel, or the sound emitted by industrial operations. Within the legal framework of the US

MMPA, disturbance is considered Level B harassment. For the purpose of this chapter, disturbance is deemed acoustic disturbance as a result of underwater sound from anthropogenic activities. For brevity, acoustic disturbance to hauled-out pinnipeds by airborne sound, such as that from overflying aircraft, is excluded in this overview.

10.3.4 Behavioral Change

Behavioral response study (BRS) designs are often followed to assess whether or not there is a significant behavioral change in an animal in response to an acoustic stimulus. BRSs in marine mammals have focused on five main research areas (Deecke 2006): (1) to determine the function of conspecific vocalizations, (2) as a method of wildlife management (e.g., using heterospecific sounds to deter animals from specific areas), (3) to study predator-prey interactions, (4) to study individual and kin recognition, and (5) to determine the response to anthropogenic noise, the focus of this chapter.

In the literature, BRSs using an anthropogenic stimulus are sometimes called "controlled exposure experiments" (CEEs), although this implies the anthropogenic stimulus is given in carefully controlled doses, which may not always be true. The experimental design is a "before, during, and after" (BDA) procedure, where the behavior of the animals is measured before, during, and after the stimulus is given. An appropriate before period provides one type of control. The before behavior is compared with the during behavior to look for a significant change. The after period allows the assessment of the animals' behavioral "recovery" and to determine if the behavioral change was short term (only in the during phase) or long term (i.e., the animals continue to display a change in behavior after the stimulus has ended). The during phase can be classified according to the "treatment" given: usually either an "active" treatment (where the sound stimulus is presented) or a "control" treatment (where no stimulus is given but everything else remains the same). The control treatment helps determine other factors that may have contributed to the behavioral response (e.g., a response to the tow vessel rather than to the towed airguns, as studied in the Behavioural Response of Australian Humpback whales to Seismic Surveys (BRAHSS) experiment; Dunlop et al. 2015, 2016; Fig. 10.6). Treatments could also be sounds from other cetaceans. Sometimes the calls of killer whales, the apex predator, are used (e.g., Allen et al. 2014). One can then compare the behavioral response to the anthropogenic stimulus with the response to a "biologically meaningful" stimulus.

Although the majority of literature on "marine mammals and man-made sounds" reports behavioral responses, carrying out a scientifically robust BRS is not easy, resulting in common errors (Campbell and Stanley 1966), which make interpretation of results and comparison among studies difficult. The experimenter might wrongly attribute an observed behavioral change to the acoustic stimulus, when, in fact, it was due to some other environmental parameter (internal validity error). A

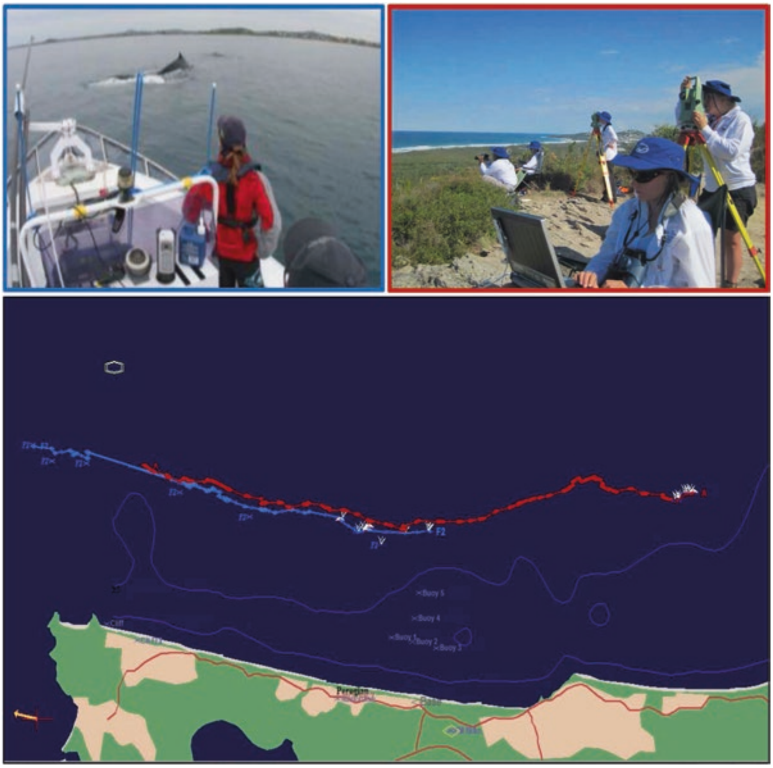


Fig. 10.6 In the Behavioural Response of Australian Humpback whales to Seismic Surveys (BRAHSS) experiment, migrating humpback whales were tracked by boat (*top left*) and from shore (*top right*), yielding tracks (*bottom*; *blue line*, boat based; *red line*, land based of the same group) that were compared between noise exposure and control conditions

common mistake is that replicates are either spatially or temporally segregated. Furthermore, conclusions are commonly generalized (e.g., to other man-made sounds, entire populations, or other species) beyond the validity of the experiment (external validity error). Exposing animals to more exemplars of the stimulus in multiple geographic regions or ecological settings and using more species will overcome this problem, although this will often require a larger number of experiments and will have cost and ethical implications.

Summaries of behavioral responses of marine mammals to man-made noise show a large variability in the received levels (differing by many tens of decibels) and the severity in the response from minor to severe (Richardson et al. 1995; Southall et al. 2007; Gomez et al. 2016). These differences are partly due to different populations, sound sources, contexts, and environments (Ellison et al. 2012; Dunlop et al. 2013). The large within-species variability might be explained by individual differences such as prior exposure (habituation versus sensitization), motivation, age, gender, and health. One would not expect all animals in a population to

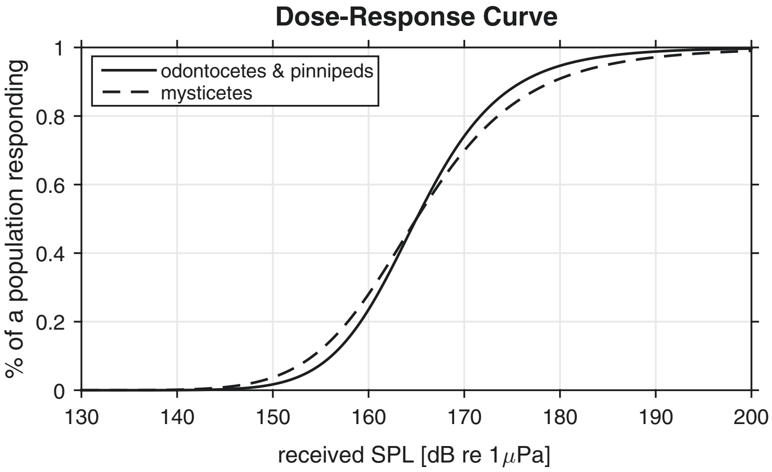


Fig. 10.7 Dose-response relationship used by the US Navy to estimate the percentage of a population of marine mammals responding to naval sonar during the Atlantic Fleet active sonar training exercises and the Gulf of Alaska Navy training activities (US Department of the Navy 2008, 2009). *SPL* sound pressure level

respond at the same received level all the time. Rather, the response of a population can be represented as a dose-response curve (Fig. 10.7), showing the range in sound levels over which a certain percentage might react (e.g., Miller et al. 2014). The usefulness of the received level as a predictor for the behavioral response remains questionable (Gomez et al. 2016), and the criteria to determine whether or not an animal responds can be difficult to define. Movement and avoidance metrics (e.g., a deviation in course, speed, or dive profile), or a change in behavioral state (e.g., from feeding to traveling) might be too broad scale. Animals may be exhibiting more subtle reactions like changes in vocal signals or fine-scale movement. The use of a multisensor digital acoustic recording tag (DTAG; Johnson and Tyack 2003), which, along with the acoustic data, simultaneously records orientation and movement of the whales, has advanced these studies, finding changes in fluke rate, duration and rate of descent and ascent (DeRuiter et al. 2013), and changes in acoustic behavior (Miller et al. 2009).

When exposed to naval low-frequency sonar, humpback whales increased the length of song (Miller et al. 2000; Fristrup et al. 2003), beaked whales ceased echolocation (Tyack et al. 2011; DeRuiter et al. 2013), and long-finned pilot whales (*Globicephala melas*) increased their call rate (Rendell and Gordon 1999). In the presence of boat noise, killer whales increased their call duration (Foote et al. 2004) and level (Holt et al. 2009); beluga whales increased their call level, reduced their call rate, and shifted the mean frequency up (Lesage et al. 1998; Scheifele et al. 2005); bottlenose dolphins (*Tursiops truncatus*) increased their whistle rate (Buckstaff 2004); and fin whales (*Balaenoptera physalus*) decreased their call duration and bandwidth (Castellote et al. 2012). These acoustic responses could be due

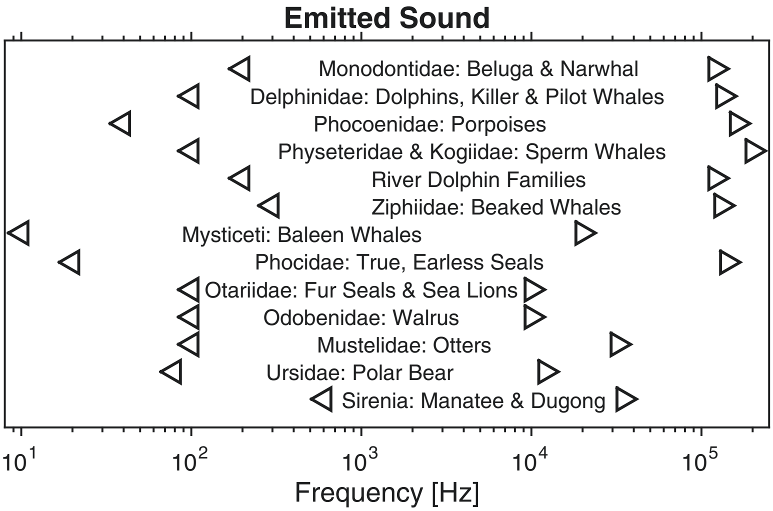


Fig. 10.8 Rough bandwidths of sound emitted by several marine mammal families. Modified from Erbe (2012)

to the boat disturbance per se, changes in context due to the presence of the boat, changes in social behavior, a response to experienced masking, or any combination of these.

10.3.5 Physiological Change

Masking

Masking is the interference of ambient noise with the detection or recognition of signals (e.g., whale communication sounds or dolphin echolocation clicks). The frequencies emitted by various groupings of marine mammals are sketched in Fig. 10.8, covering a range from 10 Hz to 200 kHz. Underwater sound of abiotic, biotic, or anthropogenic origin covers a similar range (see Figs. 10.2 and 10.3), likely making masking a common and ubiquitous phenomenon.

Various parameters relating to an animal's hearing capabilities play a role in masking (Erbe et al. 2016a). Any sound within the hearing range of an animal can be masked. The audiograms (i.e., hearing thresholds as a function of frequency) of marine mammals are summarized by Erbe et al. (2016a). The minimum thresholds recorded from individuals belonging to several species grouped by family are shown in Fig. 10.9. No audiogram exists for any of the mysticete species, sperm whales, and polar bears under water.

Masking depends on the spectral characteristics of both signal and noise at the receiver (see Dooling and Leek, Chap. 2). At a low signal-to-noise ratio, the signal

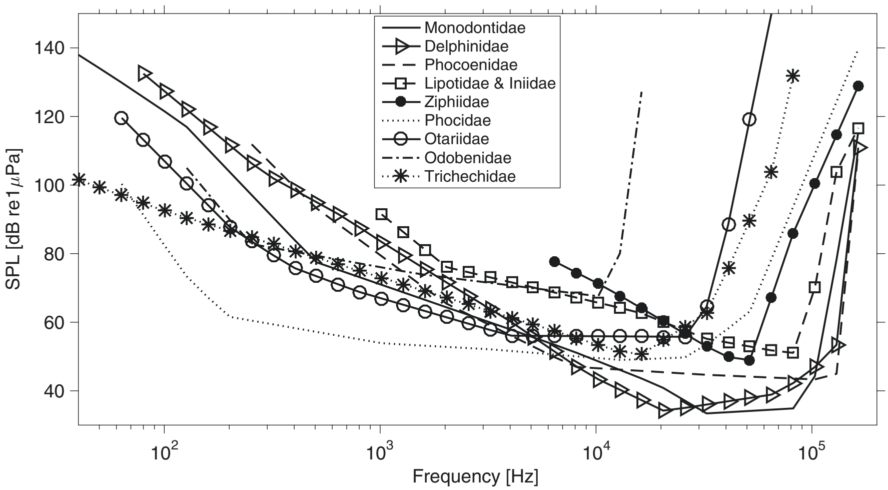


Fig. 10.9 Audiograms of several marine mammal families. The minimum thresholds recorded from any individual within these groups were interpolated to one-third octave frequencies. Updated from Erbe (2012)

might merely be detectable but not recognizable. A higher signal-to-noise ratio is needed for the animal to recognize or discriminate the signal, as known from studies with birds (Dooling et al. 2009; see also Halfwerk, Lohr, and Slabbekoorn, Chap. 8). The critical ratio (CR) is defined as the difference in the signal (tone) intensity level and the power spectrum density level of masking (white) noise at the detection threshold. CRs have been measured in a dozen marine mammal species (Erbe et al. 2016a). The CR has proven to be a strong predictor for masking in birds (Dooling and Blumenrath 2014) when the noise is continuous and broadband and the signal has strong tonal character. The CR was also a good predictor for the masking of a tonal beluga call in broadband ship noise (Erbe and Farmer 1998; Erbe 2008).

In realistic listening scenarios, signal and noise have complex spectral and temporal structures and likely arrive at the listener from different directions. If the ambient noise is amplitude modulated across a wide band of frequencies, the animal can use information from outside the band of the signal to determine when the signal occurs, simply as a difference in correlation between bands. This is called a comodulation masking release and has been demonstrated with beluga whales, bottlenose dolphins, California sea lions (*Zalophus californianus*), and harbor seals (e.g., Branstetter and Finneran 2008; Erbe 2008). If the ambient noise has quieter gaps (as in the case of strongly amplitude-modulated ship noise and natural ice-cracking noise), and if the signal is long or repetitive, the animal might detect the signal from the pieces that emerge through the intermittent noise pattern by gap listening, as shown in beluga whales (Erbe 2008). If the signal and the noise arrive from different directions, a spatial release from masking occurs based on directional hearing capabilities, as measured in bottlenose dolphins, California sea lions, and harbor seals (e.g., Turnbull 1994; Holt and Schusterman 2007). The above processes occur within the listener's auditory system. There are additional antimasking strategies that the caller can employ (Lombard effect). For most marine mammal vocalizations, their biological function is unknown, and hence an assessment of the significance of masking to vital rates is difficult.

Hearing Impairment

Although the auditory pathways to the inner ear (the cochlea) differ among marine mammal species (including the ear canal and middle ear in pinnipeds and the acoustic channel of the lower jaw in odontocetes; Norris and Harvey 1974), the neurophysiological processes are the same. As the pressure waves move through the cochlea, they cause cilia on the top of specialized sensory cells (called sensory hair cells) to bend, which causes release of a neurotransmitter that stimulates innervating eighth nerve neurons to transport the signal to the brain.

A PTS occurs when the neurophysiological process is permanently damaged (see Saunders and Dooling, Chap. 4). One of the most common ways is damage to the sensory hair cells from overexposure to sound, causing hair cell death and/or damage to the innervating neurons of the eighth nerve. A PTS is measured as a permanent increase in the hearing threshold (audiogram) at various frequencies. A TTS occurs when there is temporary impairment of the sensory hair cells; in other words, the animal's hearing threshold recovers to the normal audiogram after acoustic exposure (see Saunders and Dooling, Chap. 4). However, recent studies have shown that even a TTS may not be completely recoverable in that the nerves that transport the electrical signal to the brain may be irreversibly damaged, a damage that does not affect the audiogram but affects hearing in noisy conditions (Kujawa and Liberman 2009; Liberman 2016).

There are no data on the sound characteristics that could cause PTS in any marine mammal because, for ethical reasons, PTS has not been intentionally induced in controlled experiments. Rather, small amounts of TTS have been induced with pure tones, sonar signals, band-limited white noise, or airguns in beluga whales, bottlenose dolphins, harbor porpoises (*Phocoena phocoena*), Yangtze finless porpoises (*Neophocaena phocaenoides asiaeorientalis*), California sea lions, harbor seals, and elephant seals. The level of TTS depends on a number of factors that may include sound level, pressure rise time, duration, duty cycle, and spectral characteristics. Maximum TTS is typically seen at frequencies higher than the stimulus frequency (Kastak et al. 2008), and this difference was shown to increase with the sound level (Kastelein et al. 2014a). The relationship between exposure level and frequency agrees with equal loudness contours (Finneran and Schlundt 2013). Pinnipeds seem equally susceptible to airborne and underwater sound if exposure levels are given in terms of sensation levels (relative to the audiogram; Kastak et al. 2006). Exposures with equal cumulative SELs but different interpulse intervals produced different amounts of TTS (Kastelein et al. 2014b). TTS recovery has followed a −10log (minute) slope in some individuals (Kastak et al. 2006).

There is interesting evidence of a conditioned hearing sensitivity reduction in false killer whales (*Pseudorca crassidens*) and bottlenose dolphins whereby a brief and loud “warning” sound reduced the sensitivity to a subsequent sound (Nachtigall and Supin 2013, 2014). This mechanism might reduce the potential for hearing damage in certain circumstances.

Stress

The stress response in animals involves two different but interconnected systems (Hall 2011). The first is the sympathetic nervous system response in which the release of epinephrine and norepinephrine triggers fast physiological changes. These include an increase in heart rate, blood pressure, and gas exchange as well as a redistribution of blood to the brain and muscles, away from the stomach and other organs that are nonessential for fight or flight responses. These short-term stress responses act as adaptive countermeasures to potentially life-threatening events and can co-occur with a range of fight-or-flight behavioral responses. The second type of stress response, the hypothalamic-pituitary-adrenal (HPA) axis, is a chain of endocrine reactions, with the goal of restoring homeostasis. The whole HPA process usually begins between 3 and 5 min after the stress event and can last up to several hours after the event has ceased.

Studies with land and marine vertebrates have shown that acute stress responses can lead to a number of detrimental effects including poor body condition, poor immune function and disease resistance, decreased reproductive rates, and, in some animals, increased mortality rates (Romero and Butler 2007). Chronic (i.e., lasting days or longer) stress responses may become maladaptive if there is a prolonged activation of the stress response. For example, if animals are in a constant state of stress, particular behaviors such as the ability to find food, escape from predators, and socialize with conspecifics may be hindered (reviewed by Chrousos and Gold 1992).

Anthropogenic sources of underwater sound have the potential to cause a stress response in marine mammals. Cetaceans are subject to physiological challenges such as those associated with deep diving, prolonged fasting, thermoregulation, and osmoregulation. These processes are under endocrine control, and the breakdown of such systems may dramatically impact on the survival of an individual, especially one that lives near mammalian physiological limits (Wright et al. 2011). Acute or chronic stress in animals is quite difficult to measure given that there is potential stress associated with sampling (e.g., Ortiz and Worthy 2000; Lanyon et al. 2012). Normal diurnal (e.g., Suzuki et al. 2003) and seasonal fluctuations (e.g., Mashburn and Atkinson 2004; Myers et al. 2010) should also be taken into account. An increase in cortisol in the blood is commonly used as an indicator of stress. One of the few available studies on the physiological response to a sound stimulus involved a captive beluga whale and a captive bottlenose dolphin. Both were blood sampled before and after exposure to various levels of a seismic water gun as well as a pure tone resembling a sonar ping (Romano et al. 2004). Several physiological parameters were measured, indicating an increase in stress after exposure to high-level sounds. However, this type of study would be extremely difficult to carry out in the wild. Measuring levels of glucocorticoids from fecal (Rolland et al. 2012), blubber (Trana et al. 2015), or blow (Hogg et al. 2009) samples may be more practicable in wild animals; however, such studies carry other risks and uncertainties.

Other Physiological Effects

Sound exposure may also induce other physiological effects that are more subtle or hard to measure unless they are extensive enough to materialize in the form of increased levels of stress hormones or reduced fitness over long periods of time; it is possible that marine mammals may, in at least some cases, suffer from sound-induced neurological disorders that go undetected (Tougaard et al. 2015).

Beaked whales may be particularly susceptible to other physiological impacts. After a review of recent findings (e.g., Jepson et al. 2003; Fernandez et al. 2005) and of the anatomy and physiology of beaked whales (Rommel et al. 2006), Cox et al. (2006) suggested that rapid surfacing on sound exposure might cause gas-bubble disease in deep-diving beaked whales and explain the morbidity and mortality seen after sonar trials. Tyack et al. (2006) calculated that decompression problems are more likely to result from an abnormal behavioral response at the surface, such as repeated shallow dives, and ruled out a direct acoustic effect that triggers bubble growth. The mechanism(s) by which intense sound may lead to stranding and sometimes the death of beaked whales remains undetermined.

10.3.6 Changes in Health, Vital Rates, and Population Dynamics

Relating a change in physiology and/or behavior to a change in the animal's health (if chronic) or vital rates (if acute) is difficult and requires targeted work on the biological significance of the change. A short-term change in behavior or physiology may not necessarily be biologically significant, and therefore, it cannot be assumed that every change in behavior in response to an acoustic disturbance will lead to a change in an animal's health or vital rates. However, it cannot be assumed that because an animal or population shows little or no response, they are not vulnerable (Beale and Monaghan 2004). Even prolonged changes in behavior might not have long-term population impacts. Prolonged seismic surveys did not lead to permanent or broad-scale displacement of harbor porpoises into a suboptimal habitat (Thompson et al. 2013). However, steady increases in ambient shipping noise might have led to permanent changes in the vocalization parameters of right whales (Parks et al. 2007). The population dynamics of bottlenose dolphins were modeled and found to be unaffected by large increases in disturbance from vessels (New et al. 2013). Gray whales (*Eschrichtius robustus*) and killer whales returned after multiyear abandonment of their habitat due to anthropogenic disturbance (Bryant et al. 1984; Morton and Symonds 2002). Therefore, a species may be capable of short- and long-term modifications at the population level in response to changes in background noise conditions. Such long-term studies show that marine mammals have the ability to cope, to some extent, with changes in their acoustic environment. However, the question remains as to whether or not there is an upper limit to these changes as well as whether or not these changes have an associated cost.

It is easy to conceive different pathways from disturbance to population consequences through the PCoD model. Underwater sound might mask the song of whales, impacting mating success and ultimately population survival. Loud sound might cause TTS, putting animals at temporarily increased risk of ship strike or predation because they cannot detect the threat. Although these pathways are conceptually simple, determining the biological significance of the initial disturbance and quantifying the various transfer functions are extremely difficult.

The most tangible approach to populating the PCoD model is a bioenergetics pathway. The idea is that underwater sound disrupts foraging, leading to reduced energy intake and perhaps additional energy expenditure in avoidance, impacting maternal fitness and resulting in reduced birth rate and pup health, potentially leading to pup or adult death (Costa 2012). To fully parameterize the PCoD model, years of baseline data on foraging behavior, general health, and vital rates of individuals within that population as well as background information on the demographics and dynamics of the population are needed. Perhaps the only species for which a full PCoD model can be established at this stage is the elephant seal, for which good data on at-sea movement patterns, foraging behavior, reproductive biology, and demography are available, and the link between maternal mass and pup mass and survival is understood. In addition, this species is an ideal PCAD/PCoD candidate because all vital behaviors happen on land, with only foraging occurring at sea and hence being subject to disturbance by underwater sound (Costa et al. 2016).

Another data-rich species is the bottlenose dolphin, where some links between an acoustic stimulus and behavioral change, between health and vital rates, and between vital rates and population dynamics have been made (for a review, see New et al. 2013). The lack of data to parameterize the transfer functions for other species leads to the development of models that are based on expert opinion and simulated data. An agent-based model gives each "agent" (animal) various behavioral and/or physiological rules (including movement and dive parameters) based on a combination of observations and expert opinion. Simulations on how the agents respond to a sound stimulus are then carried out to assess the potential for impacts on the population (e.g., Nabe-Nielsen et al. 2014).

10.4 Mitigation

Reducing SELs is the most effective available means of reducing actual and potential impacts on both individuals and populations of marine mammals. Mechanisms to achieve this include reducing sound levels at the source, reducing sound propagation, or avoiding noisy activities at times and in places where sensitive species are present.

Figure 10.10 illustrates mitigation methods that involve the source (e.g., using the lowest practical power for all operations, vibratory pile driving, or alternative foundations like pile screwing instead of impact pile driving), additional sound level reduction gear installed near the source (e.g., bubble curtains or cofferdams around piles being driven), location/timing of operations (e.g., time/area closures), operational parameters (e.g., reducing ship speed and hence cavitation noise; soft start during seismic surveying and pile driving intended as a warning to marine mammals; this also includes acoustic deterrent devices), and mitigation procedures (e.g., the observation of a safety zone and reducing power or shutting down if animals

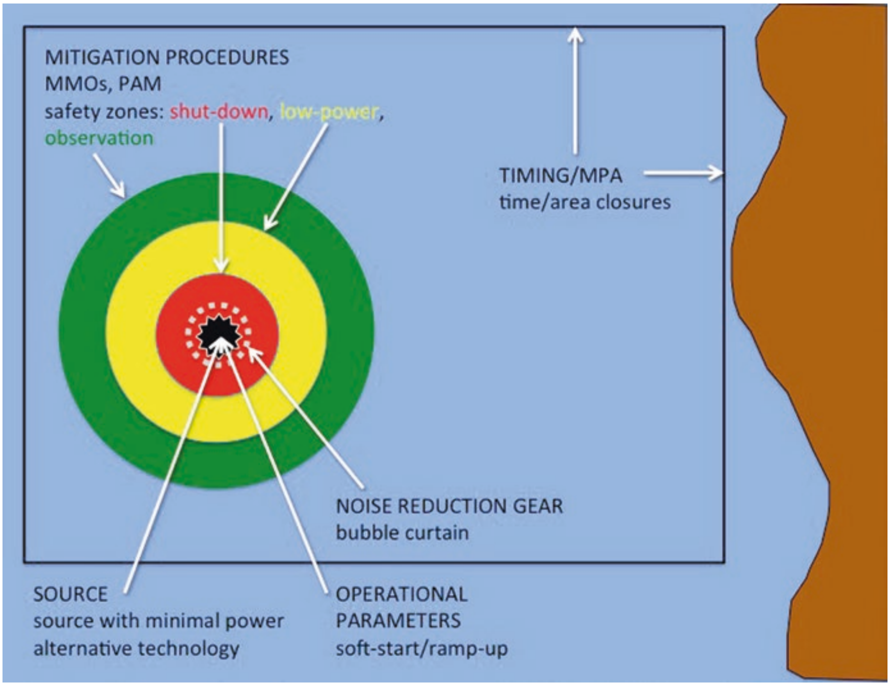


Fig. 10.10 Mitigation at the source (e.g., by using alternative, quieter technology or by modifying operational parameters), immediately near the source (e.g., by installing noise absorption gear), around the source (e.g., by using marine mammal observers [MMOs] or passive acoustic monitoring [PAM] to detect animals within certain safety zones), or over larger areas and times of year by establishing time/area closures (e.g., in marine protected areas [MPA])

enter the zone). Mitigation options for differing operations including seismic airgun surveys, naval sonar, pile driving, shipping, and explosions have been reviewed and their effectiveness and practicality have been discussed (Wright 2014). There are still many remaining questions regarding the effectiveness of the various mitigation methods.

The most commonly applied mitigation is the use of safety zones. During operations, these zones are monitored for animal presence, and if animals are sighted, often the operation switches to low power or shuts down to reduce injury to individuals. Safety zones are mostly monitored by marine mammal observers (MMOs) using binoculars. This is only practical in daylight and during good visibility. Sometimes passive acoustic monitoring is used, but it only works for vocalizing animals (Erbe 2013). Infrared, sonar, and other tools have been used to improve monitoring in certain circumstances. Common criticisms are that the size of safety zones is often determined by practicality and not (just) impact and the risk of not detecting animals. Wider impacts might happen at longer ranges and lower levels. Furthermore, these mitigation methods consider a single operation. Animals, however, are potentially exposed to multiple operations over considerable space and time. It is therefore difficult to assess, manage, and mitigate for these long-term, cumulative, and cross-border effects. A combination of wider marine spatial planning and effective mitigation measures around the source as well as collaboration among stakeholders and consistency in mitigation and regulation across jurisdictions and political borders is needed to achieve adequate management.

10.5 Regulation

Although research on underwater sound impacts on marine mammals has grown steadily over recent decades, there continue to be pressing data needs for conservation management. Furthermore, there is a significant delay in science transfer, meaning that guidance and policy lag behind the current state of scientific knowledge.

The existing legal mechanisms and guidance available to managers for reducing the impacts of individual sound sources have been reviewed (e.g., Weir and Dolman 2007; Dolman et al. 2009). Details of the limitations in existing management and mitigation, including their effectiveness, have been summarized for various jurisdictions (Parsons et al. 2009; Herschel et al. 2014).

The Joint Nature Conservation Committee (JNCC) first produced seismic guidelines in 1995. Thresholds and guidance were replicated, to various degrees, by numerous countries around the world. Guidance for a wider range of sound sources, including pile driving and explosives use, has since been developed (Joint Nature Conservation Committee 2010a, b). Currently, shipping remains unregulated with regard to sound pollution globally, but the International Maritime Organization (IMO) has issued voluntary guidelines for quieting underwater radiated sound from commercial ships (International Maritime Organization 2012). The “state of the art” in mitigation and monitoring has been described for seismic surveys (Nowacek et al. 2013).

The United States set the first thresholds for levels of sound beyond which marine mammals should not be exposed to prevent injury and disturbance under the US MMPA. The MMPA regulates Level A and B harassment (i.e., injury and disturbance respectively). Specifically, the 1994 amendments defined Level A harassment as “any act of pursuit, torment or annoyance which has the potential to injure a marine mammal or marine mammal stock in the wild” and Level B harassment as “any act of pursuit, torment, or annoyance which has the potential to disturb a marine mammal or marine mammal stock in the wild by causing disruption of behavioral patterns including, but not limited to, migration, breathing, nursing, breeding, feeding, or sheltering.”

The United States recently published an Ocean Noise Strategy (Gedamke et al. 2016) and a technical guidance providing thresholds for the onset of TTS and PTS (National Marine Fisheries Service 2016), which involved a complex review process and has taken a decade to complete. Thresholds for the onset of observable behavioral impacts have been slower, largely due to considerable variability and lack of supporting field data, although a requirement for criteria has been identified and a matrix framework that incorporates contextual factors by categorizing species, activities, and geographic areas to develop a series of step functions based on available literature documenting behavioral links was suggested (Fitch et al. 2011). This expert panel also stated that injury and behavioral harassment criteria neglect physiological stress, masking, and other factors (Fitch et al. 2011). The auditory impact criteria are now under review pursuant to Trump’s 2017 Executive Order (13795) entitled “America First Offshore Energy Strategy.”

Although the number and scale of field studies on underwater sound impacts have increased dramatically, policy is still based on studies with a few individuals of a few species, and management mostly addresses one event at a time. Mitigating immediate impacts on individuals is important, as is monitoring for long-term effects. Detecting any declines in populations, especially cryptic ones such as beaked whales, will require a large increase in monitoring effort and collaboration among countries and jurisdictions.

Conservation management is completely lacking throughout large parts of the world. Sound regulation in Antarctic and Arctic waters continues to be managed by individual nations and varies accordingly (Scott and Dolman 2006). Sound-related resolutions and statements of concern issued by various international bodies, such as the Convention on Migratory Species (CMS), have been reviewed elsewhere (Dolman et al. 2011; Simmonds et al. 2014).

The European Union (EU) first formally enshrined underwater sound in law for the determination of good environmental status (GES) under the Marine Strategy Framework Directive (2008/56/EC; Dekeling et al. 2016). Member states are required to monitor and may need to limit the amount of anthropogenic noise in European waters (van der Graaf et al. 2012). Two sound-related indicators are being defined under the Directive: one for intense sounds of short duration such as sonar, seismic surveys, and pile driving (Indicator 11.1.1) and one for low-frequency ambient noise associated primarily with shipping. No thresholds have been set and no impact indicator exists currently. Dekeling et al. (2013) outline monitoring guidance with respect to these MSFD indicators, including establishing registers of most intense sound sources and monitoring programs for ambient noise.

Fortunately, there seems to be a gradual shift from management that focuses on near-field source mitigation to prevent injury to wider, more holistic management that begins early in the planning process and is based on an effective reduction of a wider range of possible impacts. Improved early and transparent planning will help reduce the overlap between marine mammals and human activities. In addition to wide, often national-level spatial measures, habitat-based solutions such as marine protected areas can provide an effective method of reducing impacts in known areas of importance during sensitive periods (Dolman et al. 2009; Hoyt 2011). More holistic, habitat-based, multisectoral management also allows that cumulative stressors (acoustic and nonacoustic, e.g., bycatch, prey depletion, and contaminants) from different human activities be addressed. Regulators face the considerable challenge of managing these cumulative and interacting impacts with little scientific guidance.

A number of new tools are being proposed and developed to help assess the overall impact of multiple threat exposures. The United States has developed a product called CetSound (http://cetsound.noaa.gov/) to aid in the assessment and management of cumulative impacts. CetSound provides best available distribution and density maps for every cetacean species and maps of additional, biologically important areas for small resident populations and migratory species across the entire US territorial sea and exclusive economic zone. Through the CetMap process, the National Marine Fisheries Service is mapping sound levels from major chronic and intermittent sources across entire US waters.

In a pivotal case, the mass stranding of Cuvier's beaked whales was linked to naval sonar operations in the Bahamas. A prominent lawsuit followed in 2008, when a Los Angeles federal court ruled in favor of the defendant (Natural Resources Defense Council) that the US Navy should adopt specific safety measures during active sonar use to protect marine mammals (Zirbel et al. 2011). The mitigation measures included a ban on the use of sonar within 12 nautical miles of the California coast, shutdown when marine mammals entered within 2200 yards of the source, and power down during surface ducting conditions. The US Navy appealed, and the case ended up in the Supreme Court, where two of the six mitigation measures were overturned (Parsons et al. 2008). In September 2015, a US federal court settled a case that included, for the first time, spatial-temporal restrictions during active sonar and explosive use off Hawaii and California (Case No. 1:13-CV-00684-SOM-RLP).

10.6 Summary and Conclusions

Research is active on all aspects of marine mammal bioacoustics and sound impacts, including hearing and sound perception, sound production and call repertoires, behavioral responses to sound, masking, TTS, and stress. Studies are increasing in complexity, becoming multivariate, addressing complex questions in acoustic ecology, and considering cumulative exposures, potentially long-term impacts, and population consequences. As the complexity of studies grows, it is essential that researchers with diverse backgrounds collaborate. Studying marine mammals can be difficult, time consuming, and expensive, in particular in the wild. As a result, the sample size is often small, and variability and uncertainty are poorly understood. Pooling data from multiple studies is nearly impossible because of differences in measurement and analysis methodology, and reporting. Having agreed guidelines for best practice or standards would be invaluable but require dedicated effort and time to develop (Erbe et al. 2016b).

In behavioral-response experiments in the field, the experimental condition typically exposes animals to sound from an anthropogenic source, and in the control condition, animals are observed with the source present but off. The baseline study should observe the same animals in the absence of the source and its sound, assumed quiet. However, in the field, the baseline is hardly ever quiet. In many regions on Earth, the baseline and the control include ambient anthropogenic and nonanthropogenic noise. So really, these projects study the effect of additional anthropogenic noise to an already noisy ocean. How can one work out the “additional response” to the “additional noise”? This question was considered within the framework of the International Quiet Ocean Experiment (Boyd et al. 2011), which also included an interesting thought experiment: What if one could treat animals with silence? What if one could temporarily switch off all sound in a restricted habitat? What behavioral and other responses would be observed?

In order to “judge” animal responses to anthropogenic noise, it would be sensible to examine their responses to natural sounds (e.g., from wind or biological choruses). Such studies could put observed behaviors into “perspective.” It is surprising how little attention this research question has received. Another important field of research is the effectiveness of common as well as novel mitigation methods.

The big questions remain. What are the population consequences of acoustic disturbance? How do impacts accumulate over multiple exposures as well as with acoustic and nonacoustic stressors? The PCoD model provides a framework within which these questions can begin to be addressed. A combination of long-term surveillance and well-replicated and controlled experiments, including behavioral-response studies, is needed to assess population-level effects with any confidence (Nowacek et al. 2007). Implementing solutions will require innovative approaches.

As legislation and public profile have become more focused on marine sound issues in recent years, our understanding of the range of potential impacts has advanced, monitoring technologies have become more sophisticated, mitigation methods have been developed, and research funding has increased. Although the translation of science into policy is slow and somewhat convoluted, all of these advances have directed the research focus, influenced policy, and, as a result, have improved our knowledge and management of marine sound pollution in marine mammal habitats.

Compliance with Ethics Requirements
Christine Erbe declares that she has no conflict of interest.
Rebecca Dunlop declares that she has no conflict of interest.
Sarah Dolman declares that she has no conflict of interest.

References

Allen, A. N., Schanze, J. J., Solow, A. R., & Tyack, P. L. (2014). Analysis of a Blainville's beaked whale's movement response to playback of killer whale vocalizations. *Marine Mammal Science,* 30(1), 154–168.

Andrew, R., Bruce, M. H., & James, A. M. (2002). Ocean ambient sound: Comparing the 1960s with the 1990s for a receiver off the California coast. *Acoustics Research Letters Online,* 3(2), 65–70.

Au, W. W. L. (1993). *The Sonar of Dolphins*. New York: Springer-Verlag.

Beale, C. M., & Monaghan, P. (2004). Behavioural responses to human disturbance: A matter of choice? *Animal Behaviour,* 68(5), 1065–1069.

Bee, M. A., & Micheyl, C. (2008). The cocktail party problem: What is it? How can it be solved? And why should animal behaviorists study it? *Journal of Comparative Psychology,* 122(3), 235–251.

Boyd, I. L., Frisk, G., Urban, E., Tyack, P., Ausubel, J., Seeyave, S., Cato, D., Southall, B., Weise, M., Andrew, R., Akamatsu, R., Dekeling, R., Erbe, C., Farmer, D. M., Gentry, R., Gross, T., Hawkins, A. D., Li, F. C., Metcalf, K., Miller, J. H., Moretti, D., Rodrigo, C., & Shinke, T. (2011). An International Quiet Ocean Experiment. *Oceanography,* 24(2), 174–181.

Branstetter, B. K., & Finneran, J. J. (2008). Comodulation masking release in bottlenose dolphins (*Tursiops truncatus*). *The Journal of the Acoustical Society of America,* 124(1), 625–633.

Bryant, P. J., Lafferty, C. M., & Lafferty, S. K. (1984). Reoccupation of Laguna Guerrero Negro, Baja California, Mexico, by gray whales. In M. L. Jones, S. L. Swartz, & S. Leatherwood (Eds.), *The Gray Whale: Eschrichtius robustus* (pp. 375–387). Orlando, FL: Academic Press.

Buckstaff, K. C. (2004). Effects of watercraft noise on the acoustic behavior of bottlenose dolphins, *Tursiops truncatus*, in Sarasota Bay, Florida. *Marine Mammal Science,* 20(4), 709–725.

Caldwell, M. C., & Caldwell, D. K. (1965). Individualized whistle contours in bottle-nosed dolphins (*Tursiops truncatus*). *Nature,* 207(4995), 434–435.

Campbell, D. T., & Stanley, J. C. (1966). *Experimental and Quasi-Experimental Designs for Research*. Chicago, IL: Rand McNally.

Castellote, M., Clark, C., & Lammers, M. (2012). Acoustic and behavioural changes by fin whales (*Balaenoptera physalus*) in response to shipping and airgun noise. *Biological Conservation,* 147(1), 115–122.

Cato, D. H. (1978). Marine biological choruses observed in tropical waters near Australia. *The Journal of the Acoustical Society of America,* 64(3), 736–743.

Cato, D. H. (2008). Ocean ambient noise: Its measurement and its significance to marine animals. Paper presented at the Conference on Underwater Noise Measurement, Impact and Mitigation, Southampton, UK, October 14-15, 2008. *Proceedings of the Institute of Acoustics*, 30, 1-9.

Cherry, E. C. (1953). Some experiments on the recognition of speech, with one and with two ears. *The Journal of the Acoustical Society of America,* 25, 975–979.

Chrousos, G. P., & Gold, P. W. (1992). The concepts of stress and stress system disorders. Overview of physical and behavioral homeostasis. *Journal of the American Medical Association,* 267(9), 1244–1252.

Clark, C. W., Ellison, W. T., Southall, B. L., Hatch, L., Van Parijs, S. M., Frankel, A., & Ponirakis, D. (2009). Acoustic masking in marine ecosystems: Intuitions, analysis, and implication. *Marine Ecology Progress Series,* 395, 201–222.

Costa, D. P. (2012). A bioenergetics approach to developing the PCAD model. In A. N. Popper & A. Hawkins (Eds.), *The Effects of Noise on Aquatic Life* (pp. 423–426). New York: Springer-Verlag.

Costa, D. P., Schwarz, L., Robinson, P., Schick, R. S., Morris, P. A., Condit, R., Crocker, D. E., & Kilpatrick, A. M. (2016). A bioenergetics approach to understanding the population consequences of disturbance: Elephant seals as a model system. In A. N. Popper & A. Hawkins (Eds.), *The Effects of Noise on Aquatic Life II* (pp. 161–169). New York: Springer-Verlag.

Cox, T. M., Ragen, T. J., Read, A. J., Vos, E., Baird, R. W., Balcomb, K., Barlow, J., Caldwell, J., Cranford, T., Crum, L., Amico, A. D., Spain, G. D., Fernandez, A., Finneran, J., Gentry, R., Gerth, W., Gulland, F., Hidebrand, J., Houser, D., Hullar, T., Jepson, P. D., Ketten, D., MacLeod, C. D., Miller, P., Moore, S., Mountain, D. C., Palka, D., Ponganis, P., Rommel, S., Rowles, T., Taylor, B., Tyack, P., Wartzok, D., Gisiner, R., Mead, J., & Benner, L. (2006). Understanding the impacts of anthropogenic sound on beaked whales. *Journal of Cetacean Research and Management,* 7(3), 177–187.

Deecke, V. B. (2006). Studying marine mammal cognition in the wild: A review of four decades of playback experiments. *Aquatic Mammals,* 32(4), 461–482.

Deecke, V. B., Slater, P. J. B., & Ford, J. K. B. (2002). Selective habituation shapes acoustic predator recognition in harbour seals. *Nature,* 420(6912), 171–173.

Dekeling, R., Tasker, M., Ainslie, M., Andersson, M., André, M., Borsani, F., Brensing, K., Castellote, M., Dalen, J., Folegot, T., van der Graaf, S., Leaper, R., Liebschner, A., Pajala, J., Robinson, S., Sigray, P., Sutton, G., Thomsen, F., Werner, S., Wittekind, D., & Young, J. V. (2016). The European Marine Strategy: Noise monitoring in European marine waters from 2014. In A. N. Popper & A. Hawkins (Eds.), *The Effects of Noise on Aquatic Life II* (pp. 205–215). New York: Springer-Verlag.

Dekeling, R. P. A., Tasker, M. L., van der Graaf, A. J., Ainslie, M. A., Andersson, M. H., André, M., Borsani, J. F., Brensing, K., Castellote, M., Cronin, D., Dalen, J., Folegot, T., Leaper, R., Pajala, J., Redman, P., Robinson, S. P., Sigray, P., Sutton, G., Thomsen, F., Werner, S., Wittekind, D., & Young, J. V. (2013). *Monitoring Guidance for Underwater Noise in European Seas: Background Information and Annexes*. Guidance Report, Second Report of the Technical Subgroup on Underwater Noise (TSG Noise), November 2013.

DeRuiter, S. L., Southall, B. L., Calambokidis, J., Zimmer, W. M. X., Sadykova, D., Falcone, E. A., Friedlaender, A. S., Joseph, J. E., Moretti, D., Schorr, G. S., Thomas, L., & Tyack, P. L. (2013). First direct measurements of behavioural responses by Cuvier's beaked whales to mid-frequency active sonar. *Biology Letters,* 9(4), 20130223. https://doi.org/10.1098/rsbl.2013.0223.

Dolman, S. J., Weir, C. R., & Jasny, M. (2009). Comparative review of marine mammal guidance implemented during naval exercises. *Marine Pollution Bulletin,* 58, 465–477.

Dolman, S. J., Evans, P. G. H., Notarbartolo-di-Sciara, G., & Frisch, H. (2011). Active sonar, beaked whales and European regional policy. *Marine Pollution Bulletin,* 63(1–4), 27–34.

Dooling, R. J., & Blumenrath, S. H. (2014). Avian sound perception in noise. In H. Brumm (Ed.), *Animal Communication in Noise* (pp. 229–250). Berlin: Springer-Verlag.

Dooling, R. J., West, E. W., & Leek, M. R. (2009). Conceptual and computational models of the effects of anthropogenic noise on birds. Paper presented at the 5th International Conference on Bioacoustics 2009, Holywell Park, UK, March 31 to April 2, 2009. *Proceedings of the Institute of Acoustics,* 31(1), 99–106.

Dunlop, R. A., Cato, D. H., & Noad, M. J. (2010). Your attention please: Increasing ambient noise levels elicits a change in communication behaviour in humpback whales (*Megaptera novaeangliae*). *Proceedings of the Royal Society B: Biological Sciences,* 277(1693), 2521–2529.

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

Dunlop, R. A., Cato, D. H., & Noad, M. J. (2014). Evidence of a Lombard response in migrating humpback whales (*Megaptera novaeangliae*). *The Journal of the Acoustical Society of America,* 136(1), 430–437.

Dunlop, R. A., Noad, M. J., McCauley, R. D., Kniest, E., Paton, D., & Cato, D. H. (2015). The behavioural response of humpback whales (*Megaptera novaeangliae*) to a 20 cubic inch air gun. *Aquatic Mammals,* 41(4), 412–433.

Dunlop, R. A., Noad, M. J., McCauley, R. D., Kniest, E., Slade, R., Paton, D., & 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.

Ellison, W., Southall, B., Clark, C., & Frankel, A. (2012). A new context-based approach to assess marine mammal behavioral responses to anthropogenic sounds. *Conservation Biology,* 26(1), 21–28.

Erbe, C. (2008). Critical ratios of beluga whales (*Delphinapterus leucas*) and masked signal duration. *The Journal of the Acoustical Society of America,* 124(4), 2216–2223.

Erbe, C. (2011). *Underwater Acoustics: Noise and the Effects on Marine Mammals, A Pocket Handbook*, 3rd ed. Brisbane, Australia: JASCO Applied Sciences. Available at http://oalib.hlsresearch.com/PocketBook 3rd ed.pdf.

Erbe, C. (2012). The effects of underwater noise on marine mammals. In A. N. Popper & A. Hawkins (Eds.), *The Effects of Noise on Aquatic Life* (pp. 17–22). New York: Springer-Verlag.

Erbe, C. (2013). Underwater passive acoustic monitoring and noise impacts on marine fauna—A workshop report. *Acoustics Australia,* 41(1), 113–119.

Erbe, C., & Farmer, D. M. (1998). Masked hearing thresholds of a beluga whale (*Delphinapterus leucas*) in icebreaker noise. *Deep Sea Research Part II: Topical Studies in Oceanography,* 45(7), 1373–1388.

Erbe, C., & Farmer, D. M. (2000). Zones of impact around icebreakers affecting beluga whales in the Beaufort Sea. *The Journal of the Acoustical Society of America,* 108(3), 1332–1340.

Erbe, C., Reichmuth, C., Cunningham, K. C., Lucke, K., & Dooling, R. J. (2016a). Communication masking in marine mammals: A review and research strategy. *Marine Pollution Bulletin,* 103, 15–38.

Erbe, C., Ainslie, M. A., de Jong, C. A. F., Racca, R., & Stocker, M. (2016b). The need for protocols and standards in research on underwater noise impacts on marine life. In A. N. Popper & A. Hawkins (Eds.), *The Effects of Noise on Aquatic Life II* (pp. 1265–1271). New York: Springer-Verlag.

Fernandez, A., Edwards, J. F., Rodriguez, F., de los Monteros, A. E., Herraez, P., Castro, P., Jaber, J. R., Martin, V., & Arbelo, M. (2005). "Gas and fat embolic syndrome" involving a mass stranding of beaked whales (family *Ziphiidae*) exposed to anthropogenic sonar signals. *Veterinary Pathology,* 42(4), 446–457.

Finley, K. J., Miller, G. W., Davis, R. A., & Greene, C. R. (1990). Reactions of belugas, *Delphinapterus leucas*, and narwhals, *Monodon monoceros*, to ice-breaking ships in the Canadian high arctic. *Canadian Bulletin of Fisheries and Aquatic Sciences,* 224, 97–117.

Finneran, J. J., & Schlundt, C. E. (2013). Effects of fatiguing tone frequency on temporary threshold shift in bottlenose dolphins (*Tursiops truncatus*). *The Journal of the Acoustical Society of America,* 133(3), 1819–1826.

Fitch, R., Harrison, J., & Lewandowski, J. (2011). *Marine Mammal and Sound Workshop July 13 and 14, 2010*. Report to the National Ocean Council Ocean Science and Technology Interagency Policy Committee, Washington, DC.

Fletcher, J. L., & Busnel, R.-G. (Eds.). (1978). *Effects of Noise on Wildlife*. New York: Academic Press.

Foote, A. D., Osborne, R. W., & Hoelzel, A. R. (2004). Environment: Whale-call response to masking boat noise. *Nature,* 428(6986), 910. https://doi.org/10.1038/428910a.

Ford, J. K. B. (1991). Vocal traditions among resident killer whales (*Orcinus orca*) in coastal waters of British Columbia. *Canadian Journal of Zoology,* 69(6), 1454–1483.

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

Gannon, D. P., Barros, N. B., Nowacek, D. P., Read, A. J., Waples, D. M., & Wells, R. S. (2005). Prey detection by bottlenose dolphins, *Tursiops truncatus*: An experimental test of the passive listening hypothesis. *Animal Behaviour,* 69, 709–720.

Gavrilov, A., & Li, B. (2007). *Antarctica as One of the Major Sources of Noise in the Ocean*. Paper presented at the 2nd International Conference and Exhibition, Underwater Acoustic Measurements: Technologies and Results, Heraklion, Crete, June 25-29, 2007.

Gedamke, J., Harrison, J., Hatch, L., Angliss, R., Barlow, J., Berchok, C., Caldow, C., Castellote, M., Cholewiak, D., DeAngelis, M. L., Dziak, R. P., Garland, E. C., Guan, S., Hastings, S., Holt, M. M., Laws, B., Mellinger, D. K., Moore, S. E., Moore, T. J., Oleson, E., Pearson-Meyer, J., Piniak, W., Redfern, J. V., Rowles, T., Scholik-Schlomer, A., Smith, A. B., Soldevilla, M., Stadler, J., Van Parijs, S. M., & Wahle, C. (2016). *Ocean Noise Strategy Roadmap*. Boston, MA: National Oceanic and Atmospheric Administration.

Gomez, C., Lawson, J., Wright, A. J., Buren, A., Tollit, D., & Lesage, V. (2016). A systematic review on the behavioural responses of wild marine mammals to noise: The disparity between science and policy. *Canadian Journal of Zoology,* 94(12), 801–819.

Guerra, M., Thode, A., Blackwell, S., & Macrander, M. (2011). Quantifying seismic survey reverberation off the Alaskan North Slope. *The Journal of the Acoustical Society of America,* 130(5), 3046–3058.

Hall, J. E. (2011). *Guyton and Hall Textbook of Medical Physiology*, 12th ed. Philadelphia, PA: Saunders/Elsevier.

Harwood, J., King, S., Schick, R., Donovan, C., & Booth, C. (2014). A protocol for implementing the interim population consequences of disturbance (PCoD) approach: Quantifying and assessing the effects of UK offshore renewable energy developments on marine mammal populations. Report Number SMRUL-TCE-2013-014, *Scottish Marine and Freshwater Science,* 5(2). Available at http://www.gov.scot/Resource/0044/00443360.pdf.

Herschel, A., Stephenson, S., Sparling, C., Sams, C., & Monnington, J. (2014). *ORJIP Project 4, Phase 1 Use of Deterrent Devices and Improvements to Standard Mitigation During Piling*. Research Summary 300100 (2013): S00, Offshore Renewables Joint Industry Programme (ORJIP).

Herzing, D. L. (1996). Vocalizations and associated underwater behavior of free-ranging Atlantic spotted dolphins, *Stenella frontalis* and bottlenose dolphins, *Tursiops truncatus*. *Aquatic Mammals,* 22(2), 61–79.

Hogg, C. J., Rogers, T. L., Shorter, A., Barton, K., Miller, P. J. O., & Nowacek, D. P. (2009). Determination of steroid hormones in whale blow: It is possible. *Marine Mammal Science,* 25(3), 605–618.

Holt, M. M., & Schusterman, R. J. (2007). Spatial release from masking of aerial tones in pinnipeds. *The Journal of the Acoustical Society of America,* 121(2), 1219–1225.

Holt, M. M., Noren, D. P., Veirs, V., Emmons, C. K., & Veirs, S. (2009). Speaking up: Killer whales (*Orcinus orca*) increase their call amplitude in response to vessel noise. *The Journal of the Acoustical Society of America,* 125(1), EL27-EL32.

Home, E. (1812). An account of some peculiarities in the structure of the organ of hearing in the *Balaena mysticetus* of *Linnaeus*. *Philosophical Transactions of the Royal Society of London,* 102(1), 83–89.

Hoyt, E. (2011). *Marine Protected Areas for Whales, Dolphins and Porpoises*, 2nd ed. London: Earthscan.

International Maritime Organization (IMO). (2012). *Provisions for Reduction of Noise from Commercial Shipping and Its Adverse Impacts on Marine Life*. Document DE 57/17, IMO Sub-Committee on Ship Design and Equipment.

Jensen, F. B., Kuperman, W. A., Porter, M. B., & Schmidt, H. (2011). *Computational Ocean Acoustics*, 2nd ed. New York: Springer-Verlag.

Jepson, P. D., Arbelo, M., Deaville, R., Patterson, I. A. P., Castro, P., Baker, J. R., Degollada, E., Ross, H. M., Herraez, P., Pocknell, A. M., Rodriguez, F., Howie, F. E., Espinosa, A., Reid, R. J., Jaber, J. R., Martin, V., Cunningham, A. A., & Fernandez, A. (2003). Gas-bubble lesions in stranded cetaceans. *Nature,* 425(6958), 575–576. https://doi.org/10.1038/425575a.

Johnson, M. P., & Tyack, P. L. (2003). A digital acoustic recording tag for measuring the response of wild marine mammals to sound. *IEEE Journal of Oceanic Engineering,* 28(1), 3–12.

Joint Nature Conservation Committee (JNCC). (2010a). *JNCC Guidelines for Minimising the Risk of Injury and Disturbance to Marine Mammals from Seismic Surveys*. Aberdeen, UK: Joint Nature Conservation Committee.

Joint Nature Conservation Committee (JNCC). (2010b). *Statutory Nature Conservation Agency Protocol for Minimising the Risk of Injury to Marine Mammals from Piling Noise*. Aberdeen, UK: Joint Nature Conservation Committee.

Kastak, D., Holt, M. M., Mulsow, J., Kastak, C. J. R., Schusterman, R. J., & Southall, B. L. (2006). Towards a predictive model of noise-induced temporary threshold shift for an amphibious marine mammal, the California sea lion (*Zalophus californianus*). *The Journal of the Acoustical Society of America,* 120(5), 3226.

Kastak, D., Mulsow, J., Ghoul, A., & Reichmuth, C. (2008). Noise-induced permanent threshold shift in a harbor seal. *The Journal of the Acoustical Society of America,* 123(5), 2986.

Kastelein, R. A., Gransier, R., & Hoek, L. (2013). Comparative temporary threshold shifts in a harbor porpoise and harbor seal, and severe shift in a seal. *The Journal of the Acoustical Society of America,* 134(1), 13–16.

Kastelein, R. A., Schop, J., Gransier, R., & Hoek, L. (2014a). Frequency of greatest temporary hearing threshold shift in harbor porpoises (*Phocoena phocoena*) depends on the noise level. *The Journal of the Acoustical Society of America,* 136(3), 1410–1418.

Kastelein, R. A., Hoek, L., Gransier, R., Rambags, M., & 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.

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

Lanyon, J. M., Sneath, H. L., & Long, T. (2012). Evaluation of exertion and capture stress in serum of wild dugongs (*Dugong dugon*). *Journal of Zoo and Wildlife Medicine,* 43(1), 20–32.

Lesage, V., Barrette, C., Kingsley, M. C. S., & Sjare, B. (1998). The effect of vessel noise on the vocal behavior of belugas in the St. Lawrence River estuary, Canada. *Marine Mammal Science,* 15(1), 65–84.

Liberman, M. C. (2016). Noise-induced hearing loss: Permanent versus temporary threshold shifts and the effects of hair cell versus neuronal degeneration. In A. N. Popper & A. Hawkins (Eds.), *The Effects of Noise on Aquatic Life II* (pp. 1–7). New York: Springer-Verlag.

Lombard, É. (1911). Le signe de l'élévation de la voix. *Annales des Maladies de L'Oreille et du Larynx,* XXXVII(2), 101-109.

Mann, D. A., Cook-Hill, M., Manire, C., Greenhow, D., Montie, E., Powell, J., Wells, R., Bauer, G., Cunningham-Smith, P., Lingenfelser, R., Digiovanni Jr., R., Stone, A., Brodsky, M., Stevens, R., Kieffer, G., & Hoetjes, P. (2010). Hearing loss in stranded odontocete dolphins and whales. *PLoS ONE,* 5(11), e13824.

Mashburn, K. L., & Atkinson, S. (2004). Evaluation of adrenal function in serum and feces of Steller sea lions (*Eumetopias jubatus*): Influences of molt, gender, sample storage, and age on glucocorticoid metabolism. *General and Comparative Endocrinology,* 136(3), 371–381.

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

Miller, P. J. O., Johnson, M. P., Madsen, P. T., Biassoni, N., Quero, M., & 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. J. O., Antunes, R. N., Wensveen, P. J., Samarra, F. I. P., Alves, A. C., Tyack, P. L., Kvadsheim, P. H., Kleivane, L., Lam, F.-P. A., Ainslie, M. A., & Thomas, L. (2014). Dose-response relationships for the onset of avoidance of sonar by free-ranging killer whales. *The Journal of the Acoustical Society of America,* 135(1), 975–993.

Morton, A. B., & Symonds, H. K. (2002). Displacement of *Orcinus orca* (L.) by high amplitude sound in British Columbia, Canada. *ICES Journal of Marine Science,* 59(1), 71–80.

Myers, M. J., Litz, B., & Atkinson, S. (2010). The effects of age, sex, season and geographic region on circulating serum cortisol concentrations in threatened and endangered Steller sea lions (*Eumetopias jubatus*). *General and Comparative Endocrinology,* 165(1), 72–77.

Nabe-Nielsen, J., Sibly, R. M., Tougaard, J., Teilmann, J., & Sveegaard, S. (2014). Effects of noise and by-catch on a Danish harbour porpoise population. *Ecological Modelling,* 272, 242–251.

Nachtigall, P. E., & Supin, A. Y. (2013). A false killer whale reduces its hearing sensitivity when a loud sound is preceded by a warning. *Journal of Experimental Biology,* 216(12), 3062–3070.

Nachtigall, P. E., & Supin, A. Y. (2014). Conditioned hearing sensitivity reduction in a bottlenose dolphin (*Tursiops truncatus*). *Journal of Experimental Biology,* 217(16), 2806–2813.

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 Temporary Threshold Shifts*. Report by the National Oceanic and Atmospheric Administration (NOAA) and US Department of Commerce (DOC), Silver Spring, MD.

National Research Council. (1994). *Low-Frequency Sound and Marine Mammals: Current Knowledge and Research Needs*. Washington, DC: National Academies Press.

National Research Council. (2000). *Marine Mammals and Low-Frequency Sound: Progress Since 1994*. Washington, DC: National Academies Press.

National Research Council. (2005). *Marine Mammal Populations and Ocean Noise: Determining When Noise Causes Biologically Significant Effects*. Washington, DC: National Academies Press.

New, L. F., Harwood, J., Thomas, L., Donovan, C., Clark, J. S., Hastie, G., & Lusseau, D. (2013). Modelling the biological significance of behavioural change in coastal bottlenose dolphins in response to disturbance. *Functional Ecology,* 27, 314–322.

New, L. F., Clark, J. S., Costa, D. P., Fleishman, E., Hindell, M. A., Klanjcek, T., Lusseau, D., Kraus, S., McMahon, C. R., Robinson, P. W., Schick, R. S., Schwarz, L. K., Simmons, S. E., Thomas, L., Tyack, P. L., & Harwood, J. (2014). Using short-term measures of behaviour to estimate long-term fitness of southern elephant seals. *Marine Ecology Progress Series,* 496, 99–108.

Norris, K., & Harvey, G. (1974). Sound transmission in the porpoise head. *The Journal of the Acoustical Society of America,* 56(2), 659–664.

Nowacek, D. P., Thorne, L. H., Johnston, D. W., & Tyack, P. L. (2007). Responses of cetaceans to anthropogenic noise. *Mammal Review,* 37(2), 81–115.

Nowacek, D. P., Bröker, K., Donovan, G., Gailey, G., Racca, R., & Reeves, R. R. (2013). Responsible practices for minimizing and monitoring environmental impacts of marine seismic surveys with an emphasis on marine mammals. *Aquatic Mammals,* 39(4), 356–377.

Ortiz, R. M., & Worthy, G. A. J. (2000). Effects of capture on adrenal steroid and vasopressin concentrations in free-ranging bottlenose dolphins (*Tursiops truncatus*). *Comparative Biochemistry and Physiology Part A: Molecular & Integrative Physiology,* 125(3), 317–324.

Parks, S. E., Clark, C. W., & Tyack, P. L. (2007). Short- and long-term changes in right whale calling behavior: The potential effects of noise on acoustic communication. *The Journal of the Acoustical Society of America,* 122(6), 3725–3731.

Parsons, E. C. M., Dolman, S. J., Wright, A. J., Rose, N. A., & Burns, W. C. G. (2008). Navy sonar and cetaceans: Just how much does the gun need to smoke before we act? *Marine Pollution Bulletin,* 56(7), 1248–1257.

Parsons, E. C. M., Dolman, S. J., Jasny, M., Rose, N. A., Simmonds, M. P., & Wright, A. J. (2009). A critique of the UK's JNCC seismic survey guidelines for minimising acoustic disturbance to marine mammals: Best practise? *Marine Pollution Bulletin,* 58(5), 643–651.

Payne, R., & Webb, D. (1971). Orientation by means of long range acoustic signaling in baleen whales. *Annals of the New York Academy of Sciences,* 188, 110–141.

Payne, R. S., & McVay, S. (1971). Songs of humpback whales. *Science,* 173(3997), 585–597.

Rendell, L. E., & Gordon, J. C. D. (1999). Vocal response of long-finned pilot whales (*Globicephala melas*) to military sonar in the Ligurian Sea. *Marine Mammal Science,* 15(1), 198–204.

Richardson, W. J., Greene, C. R., Malme, C. I., & Thomson, D. H. (1995). *Marine Mammals and Noise*. San Diego, CA: Academic Press.

Rolland, R. M., Parks, S. E., Hunt, K. E., Castellote, M., Corkeron, P. J., Nowacek, D. P., Wasser, S. K., & Kraus, S. D. (2012). Evidence that ship noise increases stress in right whales. *Proceedings of the Royal Society B: Biological Sciences,* 279(1737), 2363–2368.

Roman, J., Altman, I., Dunphy-Daly, M. M., Campbell, C., Jasny, M., & Read, A. J. (2013). The Marine Mammal Protection Act at 40: Status, recovery, and future of US marine mammals. *Annals of the New York Academy of Sciences,* 1286, 29–49.

Romano, T. A., Keogh, M. J., Kelly, C., Feng, P., Berk, L., Schlundt, C. E., Carder, D. A., & Finneran, J. J. (2004). Anthropogenic sound and marine mammal health: measures of the nervous and immune systems before and after intense sound exposure. *Canadian Journal of Fisheries and Aquatic Sciences,* 61(7), 1124–1134.

Romero, M. L., & Butler, L. K. (2007). Endocrinology of stress. *International Journal of Comparative Psychology,* 20(2), 89–95.

Rommel, S. A., Costidid, A. M., Fernández, A., Jepson, P. D., Pabst, D. A., McLellan, W. W., Houser, D. S., Cranford, T. W., Van Helden, A. L., Allen, D. M., & Barros, N. B. (2006). Elements of beaked whale anatomy and diving physiology and some hypothetical causes of sonar-related stranding. *Journal of Cetacean Research and Management,* 7, 189–209.

Salter, R. E. (1979). Site utilisation, activity budgets, and disturbance responses of Atlantic walruses during terrestrial haul-out. *Canadian Journal of Zoology,* 57(6), 1169–1180.

Scheifele, P. M., Andrew, S., Cooper, R. A., Darre, M., Musiek, F. E., & Max, L. (2005). Indication of a Lombard vocal response in the St. Lawrence River beluga. *The Journal of the Acoustical Society of America,* 117(3), 1486–1492.

Schorr, G. S., Falcone, E. A., Moretti, D. J., & Andrews, R. D. (2014). First long-term behavioral records from Cuvier's beaked whales (*Ziphius cavirostris*) reveal record-breaking dives. *PLoS ONE,* 9(3), e92633.

Scott, K., & Dolman, S. J. (2006). *Current Noise Pollution Issues*. Paper presented at the 25th Meeting of the Convention for the Conservation of Antarctic and Marine Living Resources (CCAMLR), Hobart, Australia, October 23 to November 3, 2006.

Simmonds, M. P., Dolman, S. J., Jasny, M., Parsons, E. C. M., Weilgart, L., Wright, A. J., & Leaper, R. (2014). Marine noise pollution-Increasing recognition but need for more practical action. *Journal of Ocean Technology,* 9, 71–90.

Southall, B. L., Bowles, A. E., Ellison, W. T., Finneran, J. J., Gentry, R. L., Greene, C. R., Jr., Kastak, D., Ketten, D. R., Miller, J. H., Nachtigall, P. E., Richardson, W. J., Thomas, J. A., & Tyack, P. L. (2007). Marine mammal noise exposure criteria: Initial scientific recommendations. *Aquatic Mammals,* 33(4), 411–521.

Suzuki, M., Uchida, S., Ueda, K., Tobayama, T., Katsumata, E., Yoshioka, M., & Aida, K. (2003). Diurnal and annual changes in serum cortisol concentrations in Indo-Pacific bottlenose dolphins *Tursiops aduncus* and killer whales *Orcinus orca*. *General and Comparative Endocrinology,* 132(3), 427–433.

Thompson, P. M., Brookes, K. L., Graham, I. M., Barton, T. R., Needham, K., Bradbury, G., & Merchant, N. D. (2013). Short-term disturbance by a commercial two-dimensional seismic survey does not lead to long-term displacement of harbour porpoises. *Proceedings of the Royal Society B: Biological Sciences,* 280(1771), 20132001. https://doi.org/10.1098/rspb.2013.2001.

Tougaard, J., Wright, A. J., & Madsen, P. T. (2015). Cetacean noise criteria revisited in the light of proposed exposure limits for harbour porpoises. *Marine Pollution Bulletin,* 90(1–2), 196–208.

Trana, M. R., Roth, J. D., Tomy, G. T., Anderson, W. G., & Ferguson, S. H. (2015). Influence of sample degradation and tissue depth on blubber cortisol in beluga whales. *Journal of Experimental Marine Biology and Ecology,* 462, 8–13.

Turnbull, S. D. (1994). Changes in masked thresholds of a harbor seal *Phoca vitulina* associated with angular separation of signal and noise sources. *Canadian Journal of Zoology,* 72, 1863–1866.

Tyack, P. L. (2000). Functional aspects of cetacean communication. In J. Mann, R. C. Connor, P. L. Tyack, & H. Whitehead (Eds.), *Cetacean Societies: Field Studies of Dolphins and Whales* (pp. 270–307). Chicago, IL: The University of Chicago Press.

Tyack, P. L., Johnson, M., Soto, N. A., Sturlese, A., & Madsen, P. T. (2006). Extreme diving of beaked whales. *Journal of Experimental Biology,* 209(21), 4238–4253.

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., & Boyd, I. L. (2011). Beaked whales respond to simulated and actual navy sonar. *PLoS ONE,* 6(3), e17009.

US Department of the Navy. (2008). *Atlantic Fleet Active Sonar Training Environmental Impact Statement/Overseas Environmental Impact Statement*. Norfolk, VA: Naval Facilities Engineering Command Atlantic.

US Department of the Navy. (2009). *Gulf of Alaska Navy Training Activities Draft Environmental Impact Statement/Overseas Environmental Impact Statement*. Silverdale, WA: Naval Facilities Engineering Command Northwest.

van Bree, P. J. H., & Kristensen, I. (1974). On the intriguing stranding of four Cuvier's beaked whales, *Ziphius cavirostris* G. Cuvier, 1823, on the Lesser Antillean island of Bonaire. *Bijdragen tot de Dierkunde,* 44, 235–238.

van der Graaf, A. J., Ainslie, M. A., Andre, M., Brensing, K., Dalen, J., Dekeling, R. P. A., Robinson, S. M., Tasker, M. L., Thomsen, F., & Werner, S. (2012). *European Marine Strategy Framework Directive--Good Environmental Status (MSFD GES)*. Report of the Technical Subgroup on Underwater Noise and other forms of energy, TSG Noise & Milieu Ltd., Brussels.

Weir, C. R., & Dolman, S. J. (2007). Comparative review of the Regional Marine Mammal Mitigation Guidelines implemented during industrial seismic surveys, and guidance towards a worldwide standard. *Journal of International Wildlife Law and Policy,* 10, 1–27.

Wenz, G. M. (1962). Acoustic ambient noise in the ocean: spectra and sources. *The Journal of the Acoustical Society of America,* 34(12), 1936–1956.

Wenz, G. M. (1969). Low-frequency deep-water ambient noise along the Pacific Coast of the United States. *US Navy Journal of Underwater Acoustics,* 19, 423–444.

Williams, R., Wright, A. J., Ashe, E., Blight, L. K., Bruintjes, R., Canessa, R., Clark, C. W., Cullis-Suzuki, S., Dakin, D. T., Erbe, C., Hammond, P. S., Merchant, N. D., O'Hara, P. D., Purser, J., Radford, A. N., Simpson, S. D., Thomas, L., & Wale, M. A. (2015). Impacts of anthropogenic noise on marine life: Publication patterns, new discoveries, and future directions in research and management. *Ocean & Coastal Management,* 115, 17–24.

Wright, A. J. (2014). Reducing impacts of human ocean noise on cetaceans: Knowledge gap analysis and recommendations. Gland, Switzerland: WWF International.

Wright, A. J., Soto, N. A., Baldwin, A. L., Bateson, M., Beale, C. M., Clark, C., Deak, T., Edwards, E. F., Fernandez, A., Godinho, A., Hatch, L. T., Kakuschke, A., Lusseau, D., Martineau, D., Romero, L. M., Weilgart, L. S., Wintle, B. A., Notarbartolo-di-Sciara, G., & Vidal, M. (2007). Do marine mammals experience stress related to anthropogenic noise? *International Journal of Comparative Psychology,* 20, 274–316.

Wright, A. J., Deak, T., & Parsons, E. C. M. (2011). Size matters: Management of stress responses and chronic stress in beaked whales and other marine mammals may require larger exclusion zones. *Marine Pollution Bulletin,* 63(1–4), 5–9.

Wyatt, R. (2008). *Review of Existing Data on Underwater Sounds Produced by the Oil and Gas Industry*. Report Submitted to the Joint Industry Programme on Sound and Marine Life, London.

Zirbel, K., Balint, P., & Parsons, E. C. M. (2011). Navy sonar, cetaceans and the US Supreme Court: A review of cetacean mitigation and litigation in the US. *Marine Pollution Bulletin,* 63(1–4), 40–48.