

The Status of Science for Assessing Noise Impacts on NOAA-Managed Species

In this Appendix, we summarize the status of the science for taxonomic groups managed by NOAA (marine mammals, fish, invertebrates, and sea turtles) as it relates to the information needed to assess the risk of noise impacts at an individual, species, and ecosystem levels. Specifically, we focus on what is known about hearing, sound use, and the effects of noise exposure for these groups. Though not intended to be comprehensive, this document is meant to serve as a reference by summarizing the status of the important components of risk assessment as they stand at the time of publication, and identifying where updates may be found in the future. The NOAA Ocean Noise Strategy (Strategy) is intended to be adaptive and will be shaped by how the science evolves.

SOUND USE, DETECTION, AND PRODUCTION

Marine Mammals

Marine mammals rely on keen hearing abilities to detect, recognize and localize biologically important sounds for navigation, predation avoidance, foraging through passive listening or active echolocation, and interspecific communication in complex, 3-dimensional marine environments (e.g. Schusterman 1981; Watkins & Wartzok 1985; Tyack 1998; Wartzok & Ketten 1999; Clark & Ellison 2004; Southall et al., 2007; Au & Hastings 2008; Richardson et al., 1995). Hearing abilities are a complex function of multiple abilities and processes including: (1) absolute threshold as a function of frequency and duration; (2) individual variation; (3) motivation; (4) masking; (5) localization; and (6) frequency and intensity discrimination (Richardson et al., 1995).

The majority of studies of hearing sensitivity, spectral analysis sensitivity, frequency and intensity discrimination, directional hearing capabilities, localization abilities, and temporary threshold shifts have been conducted using behavioral responses from a small number of captive trained animals from a limited number of odontocete and pinniped species (Richardson et al., 1995; Southall et al., 2007; Au & Hastings 2008; Houser & Moore 2014; Erbe et al., 2016), though it is also important to note the contribution of NOAA Stranding Programs to the availability of otherwise challenging species for testing. Hearing test results may vary within sex and age classes, individuals with different health and disease status, populations, and species, and can be affected by individual variation and motivation (Southall et al., 2007; Au and Hastings 2008). Recent advances in Auditory Evoked Potentials (AEPs) work is allowing expansion of frequency sensitivity studies to a wider number of individuals and greater range of species from wild populations (Houser & Moore, 2014). In species where hearing abilities are difficult to measure directly (e.g. baleen whales), anatomical modeling and knowledge of sound production can provide insights into potential hearing sensitivity (e.g., anatomical studies: Houser et al., 2001; Parks et al., 2005, ; ; Cranford & Krysl 2015 vocalizations: see reviews in Richardson et al. 1995; Wartzok & Ketten 1999; Au & Hastings 2008; taxonomy and behavioral responses to sound: Dahlheim & Ljungblad 1990; Frankel 2005; see review in Reichmuth 2007).

Based on morphological and measured or estimated hearing sensitivity comparisons, Southall et al. (2007) suggests dividing marine mammals into 1 hearing groups, which have been refined by NOAA (NMFS 2016), as (1) low-frequency cetaceans (all mysticetes), (2) mid-frequency cetaceans (Monodontidae, Ziphiidae, Physteridae and many Delphinidae), (3) high-frequency cetaceans (Phocoenidae, river dolphins, Kogiidae, Cephalorhynchidae and some Lagenorhynchidae), (4) phocids, and (5) otariids.

Table A-1. Marine mammal hearing groups.

Hearing Group	Generalized Hearing Range *
Low-frequency (LF) cetaceans [†] (baleen whales)	7 Hz to 35 kHz (100 Hz to 8 kHz)**
Mid-frequency (MF) cetaceans (dolphins, toothed whales, beaked whales, bottlenose whales)	150 Hz to 160 kHz
High-frequency (HF) cetaceans (true porpoises, <i>Kogia</i> , river dolphins, cephalorhynchid, <i>Lagenorhynchus cruciger</i> and <i>L. australis</i>)	275 Hz to 160 kHz
Phocid pinnipeds (underwater) (true seals)	50 Hz to 86 kHz
Otariid pinnipeds (underwater) (sea lions and fur seals)	60 Hz to 39 kHz
* Represents the generalized hearing range for the entire group as a composite (i.e., all species within the group), where individual species' hearing ranges are typically not as broad. Generalized hearing range chosen based on ~65 dB threshold from normalized composite audiogram, with the exception for lower limits for LF cetaceans (Southall et al. 2007) and PW pinniped (approximation).	

Hearing sensitivity has been measured for a large number of species and audiograms for all studied marine mammals follow a typical mammalian U-shape with best sensitivity at the lowest points of the audiogram, a moderate slope at lower frequencies, and a strong slope at higher frequencies (Au & Hastings 2008).

In addition to hearing thresholds, frequency discrimination, localization ability, and critical ratios have been studied in a few species, as well as variables that may affect hearing thresholds (Erbe et al., 2016). Odontocetes have good frequency and intensity discrimination abilities, while frequency discrimination in otariids appears less precise than in odontocetes (Richardson et al., 1995). Odontocetes have excellent directional hearing capabilities with narrow reception beams and localization thresholds on the order of 2-4 degrees across frequencies (Au & Moore 1984). Harbor seals and otariids are known to have reasonably good directional localization abilities, but these are also less precise than those of odontocetes (Richardson et al., 1995). Across all marine mammals, critical ratios (a measure of the detectability of a tone in noise, calculated as the difference between dB level of a just detectable tone and that same spectrum of background noise) increase with increasing frequency and are low (good) by terrestrial mammal standards (Richardson et al., 1995). Across studied phocids and odontocetes, hearing thresholds increase with decreasing sound duration (below 0.1 to 1 s), similar to terrestrial mammals (Richardson et al., 1995). Animal's depth did not affect hearing sensitivity of a beluga whale, but did indicate decreased hearing sensitivity with increasing depth in a California sea lion (Ridgeway et al., 2001, reviewed in Richardson et al., 1995). Odontocetes may have learned or automatic gain control with recent evidence showing increased or decreased sensitivity in special situations (i.e., absent target and with preceding warning signal for loud signals (Nachtigall & Supin 2013, 2014), respectively) (reviewed in Houser & Moore 2014). Questions remain on the comparability of AEP and behavioral studies, and the mechanisms and impact of jawphone configuration in AEP studies (i.e. bone conduction) (summarized in Houser & Moore 2014) and there is a new American National Standards Institute group working on developing standards for odontocetes. Overall, electrical methods typically underestimate sensitivity, particularly at the lower and higher frequencies (NMFS 2016). Gender and age differences have been noted in presbycusis (age-related hearing loss) for wild *Tursiops truncatus*

(Houser and Finneran 2006; Houser et al., 2008). New hearing studies with AEPs and modeling suggest Ziphiidae and Globicephalidae hearing ranges may be different enough to distinguish them from other Delphinidae (Houser & Moore 2014).

All studied marine mammals produce complex and variable sounds which may be used in a variety of contexts including communication, navigation, courtship or territorial displays, warning signals, maintaining group structure, detecting prey, individual identification, and mother/offspring contact (Southall 2004; Edds Walton 1997; Tyack & Clark 2000; Richardson et al., 1995). These types and levels of vocalizations are summarized in the table below.

Table A-2. Summary of Marine Mammal Vocalizations.

MYSTICETES*			
Description	Frequency	Source Level	References
Calls, including simple calls, complex calls and impulsive calls (clicks, pulses, knocks, and grunts); Produced by all species; Function not completely understood (population-specific and geographic differences)	10 Hz– 1 kHz (some energy extending up as high as 24 kHz)	150-190 dB re 1 μ Pa-m	Payne & McVay 1971; Winn & Winn 1978; Ljungblad et al 1982; Payne & Payne 1985; Watkins et al. 1987; Alling & Payne 1990, Alling et al 1990; Clark 1990; Richardson et al. 1995; Payne & McVay 1997; Darling & Berube 2001; Croll et al. 2002; Oleson et al. 2003; Parks & Tyack 2005; Rankin & Barlow 2005; Au et al. 2006; McDonald et al. 2006; Oleson et al. 2007; Au & Hastings 2008; Risch et al 2013
Songs (patterned sequences of calls); Produced by blue, bowhead, fin, and humpback whales and humpback whales; For courtship or territorial displays (sex- and age-based production and variation based on behavioral state and geographic location)			
ODONTOCETES**			
Description	Frequency	Source Level	References
Frequency modulated tonal calls (whistles); Not produced by all species (non-whistling families: <i>Physteridae</i> , <i>Phocoenidae</i> , <i>Kogiadae</i> , and <i>Cephalorhynchidae</i>); For social communication (structure is highly variable among individuals and across species)	1-40 kHz (harmonics may extend to higher frequencies)	100-180 dB re 1 μ Pa-m	Caldwell & Caldwell 1965; Evans 1967; Herman and Tavolga 1980; Ford 1991; Au 1993; Richardson et al. 1995; Lammers and Au 1996; Weigart and Whitehead 1997; Möhl et al. 2003; Zimmer et al. 2005b; Au & Hastings 2008
Broadband clicks (echolocation clicks and pulsed calls); Produced by all species; For navigation and foraging (echolocation clicks are highly directional)	<1 kHz to 150 kHz (pulsed calls); 5-130 kHz (echolocation clicks for whistling families) & 90-160 kHz (non-whistling families)	220 to 230 dB re 1 μ Pa-m peak to peak (whistling families); low intensity for non-whistling families, except sperm whale: 236 dB re 1 μ Pa-m	
PINNIPEDS			
Description	Frequency	Source Level	References
Vocalize in air and underwater; For aggression or attraction, particularly for territoriality and reproduction, and mother/pup contact calls; Geographic dialects described for some species	<0.2 to 10 kHz (impulsive calls to 164 kHz)	95-193 dB re 1 μ Pa-m	Schevill & Watkins 1965; Le Boeuf & Petrinovich 1974 Richardson et al 1995, Au & Hastings, 2008
* Detection ranges of calls are a function of source level, acoustic transmission losses (which increase with increasing call frequency), and background noise levels; in general, calls can be detected for several to hundreds of kilometers (Watkins & Schevill 1979, Watkins 1981, Clark 1983, Clark 1989, Stafford et al. 1998, Clark & Gagnon 2002, Watkins et al. 2004, Wiggins et al. 2004, Moore et al. 2006, Stafford et al. 2007, Tyack 2008).			
** Detection ranges of calls are less than 1km for high-frequency clicks (Clausen et al. 2011), 1-5 km for mid-frequency clicks (Zimmer et al. 2008, Marques et al. 2009, Wiggins et al. 2012), 10-40 km for low-frequency sperm whale clicks (Barlow & Taylor 2005), and 5-10 km for whistles (Rankin et al., 2008).			

Fishes

Fishes represent the largest group of vertebrate species, more than all other vertebrate groups combined. Fishes (including larval fish) may use sound for several life processes such as navigation (Staaterman & Paris, 2013), prey and predator detection, and communication. There are more than 32,000 named species of teleost fishes (see fishbase.org) and over 800 documented species of fish are known to produce sound. However, due to the sheer number and diversity of fishes, it is likely many more fish species are capable of producing sound than what is currently known (Radford et al., 2014). In addition to sound production capabilities, a fish's ability to detect sound depends on hearing sensitivity as well as special adaptations. Sensitivity to sound also varies among fishes, and many fish species have developed sensory mechanisms that enable them to detect, localize, and interpret sounds in their environment. The ability of a fish to detect and produce sound may be based on the specific anatomy and physiology of a particular species, but may also be determined to some extent by the habitats they

occupy. As discussed in Chapters 2 and 3, sound is important in the aquatic environment and the habitats fish occupy may have their own acoustic characteristics. Although, when considering the effects of anthropogenic sound on fish species that NMFS currently regulates, we are concerned about those sound sources that have the ability to cause physical injury and mortality to the individual and whether or not these effects pose a risk to the population of a particular species of protected or managed species. These would be acute or limited in duration sound exposures such as those sounds generated during pile driving, seismic surveys and underwater blasts. However, chronic and continuous sound sources are also a concern, especially if they could result in a fitness consequence and decrease survival and recovery of managed and protected fish species. Thus understanding how fishes detect and respond to sound needs to be tied to ecologically relevant factors such as fish physiology and specific life stage needs, in conjunction with spatial patterns and distribution within the habitats they occupy. For a more comprehensive review of the science and information gaps regarding the effects of sound on fishes see Normandeau Associates 2012, Popper et al. 2012, Hawkins et al. 2014b, c, , Popper et al. 2014, Popper et al. 2016.

Fishes are able to detect and process sound signals via two independent, but related sensory systems: the auditory system and lateral line system. The lateral line system in fishes is essentially a mechanosensory system used to detect vibration and water flow. Therefore, it has been debated as to whether or not fish actually “hear” with the lateral line. Because of this, the two systems (auditory and lateral line) are often linked together into a single acousticolateralis system. There are good reasons to link the two, but the primary reason is that both systems possess mechanosensory hair cells, and both systems detect sound, albeit in different ways. However, for the purposes of this document, because the lateral line system is primarily for sound detection in the near field (Webb et al. 2008, Coombs et al. 2014). Therefore it will not be discussed further, and focus will be instead on the auditory system and other physical characteristics of fishes (e.g. presence of a swim bladder) that likely play larger roles in sound detection, response and sensitivity to most anthropogenic sound sources considered harmful.

Auditory System: The bodies of fish have approximately the same density as water, so sound pressure can pass through their bodies, with their body moving in concert with the sound pressure wave. Fish can detect both particle motion and pressure components of a sound wave. According to Popper and Fay (2010), the most common mode of hearing in fishes involves sensitivity to acoustic particle motion via direct inertial stimulation of the otoliths found in the inner ears of fishes. Otoliths are comprised of calcium carbonate, and the shape and size of otoliths can vary among species. These otoliths are denser than water and the fish's body and, as a result, “move with a different amplitude and phase” than the fish's body (Ramcharitar et al. 2006). It is the relative motion between the otolith and the sensory cells located on the epithelium of the inner ear that results in bending of the cilia on the hair cells (Hawkins and Popper 2016 pers. comm). This differential movement between the otoliths and hair cells is interpreted by the fish's brain as sound (for more details on auditory system of fishes visit: <http://www.popperlab.umd.edu/background/index.htm>).

Fish with Swim Bladders: Differences in sensitivity (both hearing and physical) to acoustic pressure are also the result of the presence and type of swim bladder, as well as proximity and linkage of the swim bladder to the ear (Popper et al. 2003, Ramcharitar et al. 2006, Braun & Grande 2008, Deng et al. 2011) and in some cases, the structure of the inner itself (Deng et al. 2011). When a sound pressure wave passing through the fish's body causes the swim bladder to move, this movement is transmitted to, and stimulates, the inner ear (described above).

Fishes with swim bladders are likely more susceptible to physical injury from underwater sound exposure than are fishes that lack swim bladders. As sound pressure waves pass through the a fish's body the swim bladder routinely expands and contracts with the fluctuating sound pressures. The air within the swim bladder is a much lower density than that of water and the fish's body , thus the air (and swim bladder) can easily be compressed by sound pressure waves traveling through the fish's body. This movement of the swim bladder can result in injury. This will be discussed further in the *physical effects* section.

There are two types of swim bladders, open vs closed (i.e., physostomous and physoclistous). This as well as the state of buoyancy may be a factor that influences the degree of injury they sustain from exposure to high sound pressure levels. For example, a deflated swim bladder could put the fish at a lower risk of injury from the sound exposure compared to a fish with an inflated swim bladder (e.g., Halvorsen et al., 2012, 2013.).

Fish without swim bladders: In general, fish species lacking a swim bladder (e.g., sharks, flatfish and some tunas), or those that have small or reduced swim bladders (such as many benthic species, including some flatfish), tend to have relatively poor auditory sensitivity, and generally cannot hear sounds at frequencies above 1 kHz. However, these species (such as plaice and dab) are capable of detecting and responding to water movement/vibration in the near field and acoustic particle motion in the far field (Sand & Bleckmann 2008, Rogers and Zeddies 2008). Limited research comparing susceptibility to physical injury between fishes with and without swim bladders indicates fishes without swim bladders may be less at risk of sustaining harm from exposure to high sound pressure levels than those that possess swim bladders (Goertner et al. 1994, Halvorsen et al. 2012a, b).

Hearing Specializations: Fishes with anatomical specializations between the swim bladder (or other gas bubble) and ear generally have lower thresholds and wider hearing bandwidths than species without such specializations. Fishes that possess connections or a close proximity between the inner ear and the swim bladder may have greater ability to detect, and therefore respond to, sound pressure. This is because the sound pressure waves cause the gas-filled spaces to vibrate, generating particle motion that stimulates the inner ear. Thus, the degree of hearing sensitivity can depend on how close the swim bladder is to the ear and how far the signal has to travel. For example, fishes belonging to clupeiform species (e.g., shad, herring, sardines, and alewives) have a pair of elongated gas ducts ending in "bullae" that extend from the swim bladder, go through the skull, and directly contact the inner ear. (Fay and Edds-Walton 2008). The presence of a bubble of compressible gas in the bullae located within close proximity to the inner ears enhances stimulation of the ear, which increases hearing sensitivity (DOSITS, 2010). Although, these hearing specializations are rather unique, and many fishes do not possess such specializations.

There are many other fishes that possess swim bladders, but with no special adaptations (Coombs and Popper 1979, Ramcharitar et al. 2006). These fish often do not have a high degree of hearing sensitivity compared to those described above. For example, Atlantic salmon (*Salmo salar*) have poor hearing sensitivity (Hawkins & Johnstone 1978, 2006). These fish are only capable of detecting low frequency tones (below 380 Hz) and particle motion rather than sound pressure.

Invertebrates

The use of sound in aquatic invertebrates has not been as widely studied as other marine animals. There remains much to be learned about invertebrate sound detection along with the potential physical and behavioral effects from sound exposure. However, we know that some species of invertebrates

(e.g., larval coral, squid, octopuses and oysters), may use sound to obtain information about their environment, and can physically orient themselves based upon the sound characteristics of the areas they occupy (Cohen 1955, Budelmann 1992, Vermeij et al 2010, Kaifu et al. 2008, Simpson et al. 2011, Normandeau Associates 2012, Hawkins et al. 2014b). Separately, some species of marine invertebrates are known to be capable of producing sounds for biological needs such as courtship, foraging, and protection from predators. One of the better known examples of marine invertebrate sound production is found in species of pistol or snapping shrimp (Verslius et al. 2000).

Although our knowledge of invertebrate “hearing” is limited, there is evidence that at least some invertebrates are able to detect vibrations and movements associated with sound production and are sensitive to low frequency sounds (Breithaupt 2002; Lovell et al., 2006; Mooney et al., 2010, 2012). Whether or not they are sensitive to sound pressure in a similar manner as other animals, like fishes, is not clear. Available data suggest that they are capable of detecting vibrations, but do not appear capable of detecting pressure fluctuations. It is currently thought that sound detection in invertebrates occurs through two types of receptors. The first is through sensory organs such as statocysts (or otocysts). Statocysts are fluid-filled structures in many invertebrates that contain sensory cilia and help maintain balance and position (i.e., equilibrium). Although there are some differences, statocysts are similar to the otoliths in fish. Because they resemble fish otoliths, it has been suggested that they may be able to detect particle motion or vibration associated with sound (Cohen 1955; Budelmann 1992, Kaifu et al. 2008). The second mechanism is through the water flow detectors or sensory hairs that aquatic invertebrates possess. Flow detectors are typically comprised of sensory cilia on the body surface of invertebrates (found on most marine crustaceans), or are hair/fan-like projections. Flow detectors are thought to be capable of detecting water-borne vibrations (Laverack 1981; Budelman & Bleckman 1988; Popper et al., 2001).

Other invertebrates are capable of detecting and responding to acoustic cues, observed by directional movement towards and settlement on substrate, or orienting themselves within their environments. A recent study conducted in North Carolina focused on Eastern oyster larvae (*Crassostrea virginica*) and use of sound to detect suitable substrate for settlement (Lillis et al., 2013). Therefore, habitat-specific sound characteristics within marine communities may represent an important settlement and habitat selection cue for estuarine invertebrates, and could help drive settlement and recruitment patterns.

Similarly, Vermeij et al. (2010) recently conducted a study focused on invertebrate sound detection and response for a species of reef coral (*Montastraea faveolata*). The researchers studied free-swimming larvae of tropical corals and were able to demonstrate that coral larvae are capable of detecting reef sounds and respond to these sounds in a directional manner through movement towards the sound source. The researchers suggest that if, like settlement-stage reef fish and crustaceans, coral larvae use reef noise as a cue for orientation and colonization, then the potential management of marine noise pollution in coral reef communities warrants more attention.

Sea Turtles

The biological significance of hearing in sea turtles remains largely unstudied, but it seems likely that they use sound for navigation, to locate prey, to avoid predators, and for general environmental awareness. Electrophysiological and behavioral studies of hearing have demonstrated that green, loggerhead, Kemp’s ridley, leatherback, and hawksbill sea turtles detect low frequency acoustic and vibratory stimuli underwater and in air <2000 Hz (Bartol et al., 1999; Dow Piniak 2012; Dow Piniak et al., 2012a; Dow Piniak et al., 2012b; Lavender et al., 2014; Martin et al., 2012; Ridgway et al., 1969). Hearing has not been measured in olive ridley or flatback sea turtles, and behavioral audiograms are only

available for loggerhead sea turtles (Lavender et al., 2012; Martin et al., 2012). Sea turtles do not appear to use sound for communication. Leatherback sea turtles have been recorded making low-frequency sighs or grunt-like sounds up to 1,200 Hz (maximum energy from 300-500 Hz) while nesting, however these sounds appear to be associated with respiration (Mrosovsky 1972; Cook & Forest 2005).

IMPACTS OF NOISE

The effects of exposure to sound on marine animals may include physical injury, physiological effects (such as adverse stress responses), behavioral modifications, or masking of important sounds (e.g., those used in communication, navigation or detection of predators or prey). Disturbances from noise may be relatively short-term and spatially limited, resulting in more obvious direct effects such as easily detectable behavioral changes, or they may be more subtle, such as rises in background noise spanning months and large areas, which may lead to chronic effects that are more difficult to detect, such as a reduced ability to detect prey. The nature and scope of the likely effects from noise disturbances are dependent upon the context of the exposures and the details of any acoustic habitat impacts; however, it is important to understand that these impacts can, either individually or in combination, effect the reproduction and survival of individual marine animals, which can in turn lead to effects on populations. Additionally, the cumulative impacts from other stressors in combination with noise can have further negative energetic burdens or impacts on health that contribute to decreases in individual fitness.

Marine Mammals

Physical Effects: Exposure to noise has the potential to affect the inner ear and hearing. Noise-induced threshold shifts are defined as increases in the threshold of audibility (i.e., the sound has to be louder to be detected) of the ear at a certain frequency or range of frequencies (ANSI 1995; Yost 2000), i.e., a loss in hearing sensitivity. Threshold shifts can be temporary (TTS) or permanent (PTS) and are typically expressed in decibels (dB). Threshold shifts result from a variety of mechanical (via physical damage) and metabolic (via inner ear hair cell metabolism, such as energy production, protein synthesis, and ion transport) processes within the auditory system. The mammalian cochlea is believed to be highly conserved between terrestrial and marine mammals (Wartzok & Ketten 1999; Ketten 2000). Thus, as with other mammals, noise-induced hearing loss occurs at lower thresholds for impulsive versus non-impulsive sound sources.⁸ Additionally, it is known that not only level of exposure but also duration of exposure plays a critical role in determining the amount of threshold shift and subsequent recovery.

Currently, TTS data only exist for four species of cetaceans (bottlenose dolphins, belugas, harbor porpoises, and Yangtze finless porpoises) and three species of pinnipeds (Northern elephant seal, harbor seal, and California sea lion) exposed to a limited number of sound sources (i.e., mostly tones and octave-band noise) in laboratory settings (Finneran 2015). In general, harbor seals (Kastak et al., 2005; Kastelein et al., 2012a) and harbor porpoises (Lucke et al., 2009; Kastelein et al., 2012b) have a lower TTS onset than other measured pinniped or cetacean species. Additionally, the existing marine mammal TTS data come from a limited number of individuals within these species. There are no data available on noise-induced hearing loss for mysticetes, which is not surprising since there are no direct measurements of hearing for any of these species. PTS data (unexpected) only exists for a single harbor

⁸ **Impulsive:** Sound sources that produce sounds that are typically transient, brief (less than 1 second), broadband, and consist of high peak sound pressure with rapid rise time and rapid decay (ANSI 1986; NIOSH 1998; ANSI 2005). They can occur in repetition or as a single event. **Non-impulsive:** Sound sources that produce sounds that can be broadband, narrowband or tonal, brief or prolonged, continuous or intermittent) and typically do not have a high peak sound pressure with rapid rise time that impulsive sounds do.

seal (Kastak et al., 2008). For a summary of marine mammal noise-induced hearing loss studies, see the NMFS Acoustic Guidance ([NMFS 2016](#)).

For explosions, there is concern with not only the effects from exposure to the acoustic waves generated but also from exposure to shock wave pulses. These pulses typically have short durations and high peak pressures that may damage internal organs (see Urick 1983; Ross 1987). Air-filled body cavities, such as lungs or the gastrointestinal tract, are particularly susceptible to injury from these shock wave pulses as they pass through the boundary of two different media (i.e., from water to air-filled cavities; Yelverton et al., 1973; Goertner 1982). Bubble pulses (series of pressure pulses following a shock wave pulse generated close to explosions) are also capable of inducing physical damage (Urick 1983). Animals are most susceptible to physical injury from explosives when they are the same depth as the explosive charge (Goertner 1982). There have been incidents where marine mammals were exposed to explosives either intentionally or by accident (reviewed in Danil & St. Leger 2011).

Finally, gas bubble lesions and fat emboli (similar to those associated with human decompression sickness) have been reported in beaked whale species that stranded coincident (in space and time) with naval activities involving the use of mid-frequency sonar (Jepson et al., 2003; Fernández et al., 2005; Fernández et al., 2012). Currently, these lesions/emboli are believed to result from behavioral responses to sonar exposure (e.g., change in dive profile as a result of an avoidance reaction), rather than direct physical effects associated with sonar exposure (Cox et al., 2006; Tyack et al., 2006; Zimmer and Tyack 2007).

Behavioral Effects: Exposure to anthropogenic sound can result in a multitude of behavioral effects, ranging from no or minor effects (such as minor or brief avoidance or changes in vocalizations), to those being more potentially severe or sustained (e.g., abandonment of higher quality habitat), and even, in certain circumstances, those that can combine with physiological effects or result in secondary responses that lead to stranding and death. Assessing the severity of behavioral effects of anthropogenic sound exposure on marine mammals presents a set of unique challenges, which arise from the inherent complexity of behavioral responses. Responses can depend on numerous factors, including intrinsic, natural extrinsic (e.g., ice cover, prey distribution), or anthropogenic, as well as the interplay among factors (Archer et al., 2010). Behavioral reactions can vary not only among individuals but also within an individual, depending on previous experience with a sound source, hearing sensitivity, sex, age, reproductive status, geographic location, season, health or disease status, social behavior, or context (Ellison et al., 2012). Responses can also vary depending on characteristics associated with the sound source (e.g., whether it is moving or stationary, number of sound sources, distance from the sound source) and the potential of source and individuals co-occurring temporally and spatially (Richardson et al., 1995; NRC 2003; Wartzok et al., 2004; NRC 2005; Southall et al., 2007).

Not all behavioral responses have the same consequences. Those that have the potential to affect vital rates or have fitness consequences (effects on growth, reproduction, and survival) can lead to potential population effects and are deemed to have more serious impacts (NRC 2005). However, basic baseline behavioral assessments (e.g., how an animal normally behaves without anthropogenic sound exposure within various contexts or how detected behaviors relate to the individual in a broader context) are also often lacking in marine mammal acoustical studies, which makes it difficult to assess severity of changes associated with anthropogenic sound exposure (Tyack 2009). Furthermore, some species have been identified as being particularly sensitive to sound exposure (i.e., demonstrate behavioral harassments at lower received levels than other species), namely beaked whale species and harbor porpoises (e.g., Southall et al., 2007; Olesiuk et al., 2002; Tyack et al., 2011).

Most data available on marine mammal behavioral responses to anthropogenic sound, especially for mysticetes, comes from exposure to seismic or drilling activities (behavioral data reviewed in Richardson et al., 1995; Southall et al., 2007; Nowacek et al., 2007; OSPAR 2009). For odontocetes, most behavioral data come from exposure to acoustic deterrent or harassment devices (ADDs or AHDs) and recent data on exposure to mid-frequency tactical sonars. Overall, the behavioral responses of pinnipeds to underwater sound sources have been the least studied. Additionally, there is an overall paucity of data on behavioral responses of marine mammals exposed to pile driving activities (both impact and vibratory), especially associated with smaller nearshore projects (i.e., more data available for a limited number of species exposed to pile driving associated with wind farm development in Europe). It is also important to note, that unlike marine mammal TTS studies that are typically published in peer-reviewed journals, marine mammal behavioral data are found in a variety of published and unpublished documents (e.g., monitoring reports, technical reports), with varying levels of quality.

Masking and Acoustic Habitat Impacts: Masking is the interference in the detection, recognition or discrimination of an acoustic signal (e.g., intraspecific communication and social interactions, prey detection, predator avoidance, and navigation) by the presence of another (e.g., natural (snapping shrimp, wind, waves, precipitation) or anthropogenic noise (shipping, sonar, exploration))(Houser & Moore 2014). The ability of a noise source to mask biologically important sounds depends on the noise source characteristics and the important signal characteristics (SNR, temporal variability, direction) as a function of each other, an animal's hearing abilities (sensitivity, frequency range, critical ratios, frequency discrimination, directional discrimination, age or TTS hearing loss), and ambient noise and propagation conditions (Erbe et al., 2016). Studies of a few captive trained bottlenose dolphins, beluga whales, and several pinniped species suggest, (1) as for other mammals, increasing critical ratio (i.e. wider filter width) trends with increasing frequency, (2) species-specific differences exist in critical ratios and hence the ability to cope with masking noises (but note low sample sizes), (3) directional hearing and localization abilities are strong beyond 4-5 degrees, and (4) frequency discrimination abilities are frequency dependent and better than those of humans (on the order of 0.01 to 8 kHz between 1 and 80 kHz) (Richardson et al., 1995). Masking can be reduced in situations where the signal and noise come from different directions (Richardson et al., 1995), if mammals compensate (e.g., Lombard effect, frequency shifts, multiple looks, extended durations/modulations, spatial release) (Erbe in Houser & Moore 2014), or through amplitude modulation of the signal (Branstetter, in Houser & Moore 2014).

Fishes

Physical Effects—Auditory tissue damage can occur in fishes from exposure to high intensity sounds. Injury may also occur for fishes exposed to high levels or continuous sound, manifested as a loss of hair cells, located on the epithelium of the inner ear (Popper and Hastings 2009). These hair cells are capable of sustaining injury or damage that may result in a temporary decrease in hearing sensitivity or temporary threshold shifts (TTS). Exposure to loud sounds for a few minutes or hours has been shown to cause TTS in fishes. TTS is considered a non-injurious temporary reduction in hearing sensitivity. However, this type of noise-induced hearing loss in fishes is generally considered recoverable, as fish possess the ability to regenerate damaged hair cells (Smith et al., 2006), unlike mammals. Permanent hearing loss has not been documented in fishes. A TTS may last several minutes to several weeks and the amount of hearing loss may be related to the intensity and duration (including multiple exposures) of the sound source compared to the hearing threshold at the same frequencies.

It should be noted, however, several studies conducted that demonstrate TTS in fishes after exposure to sound did not correlate the TTS with actual ear tissue damage (Scholik and Yan 2001, Popper et al.

2005, Popper et al. 2007, Song et al. 2008). Some of these studies did indicate, however, that TTS may persist and last for several days past exposure. Therefore, an important consideration in examining the effects of TTS in fishes is determining what level of hearing loss has significant implications for behavior and any associated fitness consequences, such as preventing individuals from detecting biologically relevant signals.

Other studies have been conducted regarding structural damage on fish inner ears, although these studies did not correlate damage to TTS (e.g. Enger 1981, Hastings et al. 1996, McCauley et al., 2003). As with TTS, the degree of injury and duration of time it takes for a fish to heal these injuries may affect behavior or other necessary life functions.

Fish may be injured or killed when exposed to high levels of underwater sound, such as those generated by impulsive sound sources from pile driving or underwater explosions. Pathologies of fishes associated with very high sound level exposure and drastic changes in pressure are collectively known as *barotraumas*. As described previously, sound pressure waves can pass through a fish's body and cause the swim bladder to routinely expand and contract with the fluctuating sound pressures. At exposure to high sound pressure levels, such as with pile driving, the swim bladder may rapidly and repeatedly expand and contract, and pound against the internal organs. This pneumatic pounding may result in hemorrhage and rupture of blood vessels and internal organs, including the swim bladder, liver and kidneys. External damage has also been documented, evident with loss of scales, hematomas in the eyes, base of fins, etc. (Yelverton et al. 1975, Wiley et al. 1981, Linton et al. 1985, Godard et al. 2008, Carlson et al. 2011, Halvorsen et al. 2012a, Halvorsen et al. 2012b, Casper et al. 2012). Fishes can survive and recover from some injuries, but in other cases, death can be instantaneous, occur within minutes after exposure, or occur several days later.

In addition to the presence of a swim bladder, the level or degree of severity of injury a fish sustains may also be dependent upon the amount of air (state of buoyancy) in the swim bladder during sound exposure (Govoni et al. 2003, Halvorsen 2012a, Stephenson et al. 2010, Carlson 2012) as well as the physiological state of fish at exposure. For example, a deflated swim bladder (negatively buoyant) could put the fish at a lower risk of injury from the sound pressure exposure compared to a fish with an inflated swim bladder (positively buoyant).

Beyond effects associated with changes in pressure, more research is needed to understand the potential of injury from sources with high levels of particle motion, like various impulsive sources (Popper et al. 2014). Finally, additional physiological effects to fishes from exposure to human-made sound were increases in stress hormones or changes to other biochemical stress indicators (e.g., Sverdrup et al. 1994, Santulli et al. 1999, Wysocki et al., 2006, Nichols et al., 2015).

Behavioral Effects: Underwater sounds have been shown to alter the behavior of fishes (see review by Hastings & Popper 2005; Hawkins et al. 2012; Popper et al., 2014), although there is significant variation between species. Observed behavioral changes from exposure to human-made sound may include startle responses, changes in swimming directions and speeds, increased group cohesion and bottom diving (Engas et al., 1995, Wardle et al., 2001, Mitson & Knudsen 2003, Boeger et al., 2006, Sand et al., 2008, Neo et al. 2014) "alarm," detected by Fewtrell et al. (2003) and Fewtrell and MacCauley (2012). The startle response in fishes is a quick burst of swimming that may be involved in avoidance of predators (Popper 1997). A fish that exhibits a startle response or some of the other behaviors may not necessarily be injured, but is exhibiting behavior that suggests it perceives a stimulus indicating potential danger in its immediate environment. Therefore, these type of responses likely do not have a fitness

consequence for the individual unless the reaction increases susceptibility to predation or some other negative effect. However, fish do not exhibit a startle response or some of the other behaviors every time they experience a strong hydroacoustic stimulus.

Other potential changes include reduced predator awareness and reduced feeding (Voellmy et al. 2014, Simpson et al. 2015), or changes in distribution in the water column or schooling behavior (e.g., Skalski et al., 1992, Feist et al., 1992, Engås et al., 1996, Engås & Løkkeborg 2002, Slotte et al., 2004). The potential for adverse behavioral effects will depend on a number of factors, including the sensitivity to sound, the type and duration of the sound, as well as life stages of fish present in the areas affected by underwater sound.

It is worth a note of caution to say that most data available on behavioral responses of fishes to anthropogenic sound has been obtained through controlled, laboratory studies. In other cases behavioral studies have been conducted in the field, albeit with caged fish. Hawkins and Popper (2014) and Hawkins et al. (2014a) have demonstrated that caged fish do not show normal behavioral responses which makes it difficult extrapolating caged fish behavior to wild, unconfined fishes. It is also important to note, that some of the information regarding fish behavior while exposed to anthropogenic sounds has been obtained from unpublished documents such as monitoring reports, grey literature or other non-peer reviewed documents with varying degrees of quality.

Masking: The frequency, received level, and duration of the sound exposure determine the potential degree of auditory masking. Similar to hearing loss, the greater the degree of masking, the smaller the area becomes within which an animal can detect biologically relevant sounds such as those required to attract mates, avoid predators or find prey (Slabbekoorn et al. 2010, Dooling et al. 2015). Because the ability to detect and process sound may be important for fish survival, anything that may significantly prevent or affect the ability of fish to detect, process or otherwise recognize a biologically/ecologically relevant sound could decrease chances of survival. For example, some studies on anthropogenic sound effects on fishes have shown that the temporal pattern of fish vocalizations (e.g., sciaenids and gobies) may be altered (Parsons et al., 2009) when fish are exposed to sound-masking. This may indicate fish are able to react to noisy environments by exploiting “quiet windows” (Lugli 2003, 2009) or are moving from affected areas and congregating in areas less disturbed by nuisance sound sources. In some cases, vocal compensations occur, such as increases in the number of individuals vocalizing in the area, or increases in the pulse/sound rates produced (Picciulin et al., 2012). Vocal compensations could have an energetic cost to the individual which may lead to a fitness consequence such as affecting their reproductive success or increase detection by predators (Bonacito et al., 2001; Amarin et al., 2002).

Invertebrates

Anthropogenic noise in the marine environment may cause physical damage to invertebrates through damaging the hair cells in their statocysts. Researchers in Spain (Andre et al., 2011, Solé et al. 2013) showed acoustic trauma to squid and octopuses exposed to the high-intensity, low-frequency sounds (50 – 400 Hz).. Exposure to these sounds caused hair cell damage in the statocyst which, over time, became more severe resulting in the appearance of lesions several hours after exposure to the sound source. The research indicates that continuous sound exposure may cause severe acoustic trauma to these species. Anthropogenic sound exposure may also affect development of some invertebrate species and increase mortality rates for certain lifestages (Nedelec et al. 2014). Very little is known about invertebrate behavior associated with anthropogenic sound exposure. However, recent research indicates marine invertebrates may respond to sound in several ways such as with directional movement towards biologically relevant sounds (Vermeij et al. 2010, Simpson et al. 2011) or through

“inking, jetting and rapid coloration changes,” which are escape responses demonstrated with cuttlefish by Samson et al. (2014). This same study also found that cuttlefish were able to habituate to repeated sound levels over a 30 minute period. It is not currently known whether or not masking occurs in invertebrates. However, masking could be considered a potential effect of anthropogenic sound on marine invertebrates if the sound prevents the detection of low-frequency vibrations or other biologically relevant sounds.

Sea Turtles

We understand very little about the impacts of noise on sea turtles. No research has been conducted on the physiological effects of noise on sea turtles. Very little data exist on the behavioral responses of sea turtles to noise. However, of the studies available, many concluded that sea turtles change their behavior in some way in response to noise. Most sea turtle behavioral response studies have examined the response of sea turtles to sounds produced by seismic airguns (Moein et al., 1995, observed avoidance and then habituation; O’Hara & Wilcox, 1990, observed some turtles responding, but others not responding; McCauley et al., 2000 observed increased swimming and erratic behavior in response to approaching airguns; Weir 2007 observed no significant change in sea turtles visually sighted near active and inactive airgun arrays; and DeRuiter and Doukara, 2012, observed diving response to airguns). One additional study observed that green turtles were more likely to avoid approaching high speed vessels, rather than those travelling at low or moderate speeds, however, the authors did not measure source or received levels of sound (Hazel et al., 2007). To date, all studies have focused on evaluating the behavioral responses of loggerhead or green sea turtles.

No information exists on the impacts of masking important biological cues or deterioration of acoustic habitat for sea turtles. We do not understand how noise impacts populations, survivorship or fecundity, nor do we understand the cumulative impacts of noise on individuals or populations when combined with other stresses (bycatch, climate change, etc.).

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