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. 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; Au & Hastings 2008; Houser & Moore 2014), 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, 2007; Cranford 2012; 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 five functional hearing groups, which have been refined by NOAA (NOAA 2013), 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 functional hearing groups.

<table>
<thead>
<tr>
<th>Functional Hearing Group</th>
<th>Functional Hearing Range (best hearing)*</th>
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<tbody>
<tr>
<td>Low-frequency (LF) cetaceans (baleen whales)</td>
<td>7 Hz to 25 kHz (100 Hz to 8 kHz)**</td>
</tr>
<tr>
<td>Mid-frequency (MF) cetaceans (dolphins, toothed whales, beaked whales, bottlenose whales)</td>
<td>150 Hz to 160 kHz (10 to &gt;100 kHz)**</td>
</tr>
<tr>
<td>High-frequency (HF) cetaceans (true porpoises, <em>Kogia</em>, river dolphins, cephalorhynchid, <em>Lagenorhynchus cruciger</em> and <em>L. australis</em>)</td>
<td>200 Hz to 180 kHz++</td>
</tr>
<tr>
<td>Phocid pinnipeds (true seals)</td>
<td>75 Hz to 100 kHz (1 to 50 kHz)***</td>
</tr>
<tr>
<td>Otariid pinnipeds (sea lions and fur seals)</td>
<td>100 Hz to 48 kHz (2 to 40 kHz)****</td>
</tr>
</tbody>
</table>

* Represents frequency band of hearing for entire group as a composite (i.e., all species within the group), where individual species' functional hearing ranges are typically not as broad and best hearing ranges may be more variable.
+ Estimated hearing range for low-frequency cetaceans is based on behavioral studies, recorded vocalizations, and inner ear morphology measurements. No direct measurements of hearing ability have been successfully completed.
** (Ketten et al., 2007; Au et al., 2006; Houser et al., 2001; Parks et al., 2005, 2007; Ketten et al 1998)
++ Functional hearing measured across 15 studied species: (Johnson 1967; Finneran et al., 2005; White et al., 1979; Houser et al., 2008; Popov et al., 2007; Kastelein et al., 2003; Nachtigall et al., 2008; Nachtigall et al., 2005; Szymanski et al., 1999; Yuen 2005; Touhey-Moore et al., unpublished; Finneran et al., 2009; Pacini et al., 2011; Schlundt et al., 2011; Pacini et al., 2010; reviewed in Southall et al., 2007; Finneran and Jenkins 2012). Best hearing: (Richardson et al., 1995; Au and Hastings 2008).
+++ Across 4 studied species (*Kastak, 2002; Popov et al., 2005; Popov and Supin 1990a,b, reviewed in Southall et al., 2007; Finneran & Jenkins 2012).
**** Functional hearing: (Kastak & Schusterman, 1999; Kastelein et al., 2009; Mähl, 1967; Reichmuth 2008; Terhune & Ronald, 1971; 1972), best hearing: (Richardson et al., 1995)
(1995)
**** Functional hearing: (Babushina et al., 1991; Kastak & Schusterman 1998; Kastelein et al., 2005; Moore & Schusterman 1987; Mulsow & Reichmuth 2007; Mulsow et al., 2011a; Mulsow et al., 2011b; Schusterman et al., 1972), best hearing (Richardson et al., 1995)

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). Audiograms of 10 pinniped species exhibit a broader U-shape and decreased sensitivity compared with those of odontocetes, and better sensitivity in water than in air (Au & Hastings 2008, Richardson et al., 1995).

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. 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). 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. Gender and age differences have been noted in presbycusis (age-related hearing loss) for wild Tursiops truncatus. 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, finding food, 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.

<table>
<thead>
<tr>
<th>MYSTICETES*</th>
<th>Description</th>
<th>Frequency</th>
<th>Source Level</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>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)</td>
<td>10 Hz–1 kHz (some energy extending up as high as 24 kHz)</td>
<td>150-190 dB re 1 µPa-m</td>
<td>Payne &amp; McVay 1971; Winn &amp; Winn 1978; Lungblad et al. 1982; Payne &amp; Payne 1985; Watkins et al. 1987; Alling &amp; Payne 1990; Alling et al. 1998; Clark 1990; Richardson et al. 1995; Payne &amp; McVay 1997; Darling &amp; Benube 2001; Croll et al. 2002; Oleson et al. 2003; Pahoa &amp; Tyson 2005; Rankin &amp; Barlow 2005; Au et al. 2006; McDonald et al. 2006; Oleson et al. 2007; Au &amp; Hastings 2008; Risch et al. 2013</td>
<td></td>
</tr>
<tr>
<td>Songs (patterned sequences of calls); Produced by blue, bowhead, fin, and humpback whales and humpback calves; For courtship or territorial displays (sex- and age-related variation and production based on behavioral state and geographic location)</td>
<td></td>
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<td></td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>ODONTOCETES**</th>
<th>Description</th>
<th>Frequency</th>
<th>Source Level</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency modulated tonal calls (whistles); Not produced by all species (non-whistling families: Physeteridae, Phycoenidae, Kogiidae, and Cephalorhynchidae); For social communication (structure is highly variable among individuals and across species)</td>
<td>1-40 kHz (harmonics may extend to higher frequencies)</td>
<td>100-180 dB re 1 µPa-m</td>
<td>Caldwell &amp; Caldwell 1965; Evans 1967; Herman and Tavolga 1980; Ford 1991; Au 1993; Richardson et al. 1995; Lammers and Au 1996; Weggel and Whitehead 1997; Mehl et al. 2003, Zimmer et al. 2005b; Au &amp; Hastings 2008</td>
<td></td>
</tr>
<tr>
<td>Broadband clicks (echolocation clicks and pulsed calls); Produced by all species; For navigation and foraging (echolocation clicks are highly directional)</td>
<td>&lt;1 kHz to 150 kHz (pulsed calls); 5-130 kHz (echolocation clicks for whistling families) &amp; 90-160 kHz (non-whistling families)</td>
<td>220 to 230 dB re 1 µPa-m peak to peak (whistling families); low intensity for non-whistling families, except sperm whale: 236 dB re 1 µPa-m</td>
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</table>

<table>
<thead>
<tr>
<th>PINNIPEDS</th>
<th>Description</th>
<th>Frequency</th>
<th>Source Level</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>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</td>
<td>&lt;0.2 to 10 kHz (impulsive calls to 164 kHz)</td>
<td>95-193 dB re 1 µPa-m</td>
<td>Schevill &amp; Watkins 1965; Le Boeuf &amp; Phipps 1974; Richardson et al. 1995, Au &amp; Hastings, 2008</td>
<td></td>
</tr>
</tbody>
</table>


** Detection ranges of calls are less than 1 km 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).

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**Fish**

Fish represent the largest group of vertebrate species, more than all other vertebrate groups combined. Fish (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. 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.

Although only a mere fraction of the total number of fishes are documented as producing sound, some general inferences can be made regarding sound use and fish hearing capabilities based on specific anatomy and physiology common to certain fish taxa. Therefore, a broad grouping based on fish taxa and what we know about hearing and sound production within these taxa can be made.
Fish 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. However, 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 particle motion, albeit in different ways. We will discuss each system here, but more focus is given to the auditory system since it likely plays a larger role in sound detection and response to most anthropogenic sound sources considered harmful, compared to the lateral line system.

**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. 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 fish. 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 more slowly in response to traveling sound waves compared to the fish’s body. The difference between the motion of the otoliths and the fish’s body causes displacement of the otoliths and “bending” of sensory cilia on hair cells located on the epithelium of the fish inner ear. 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 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. Fishes with swim bladders are far more sensitive to sound, and therefore more susceptible to injury from underwater sound exposure than are fishes that lack swim bladders. The type, proximity and connection of the swim bladder to the ear in fishes will determine the degree of sensitivity (e.g., Popper et al. 2003; see Braun & Grande 2008 for review). 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. Compression of the air causes the volume of the swim bladder to cyclically change (reverberate) in reaction to fluctuating sound pressure waves. Therefore, movements of the swim bladder wall (particle motion) are transmitted to, and stimulate, the inner ear (described above).

There are two types of swim bladders, physostomous and physoclistous. Fish with physostomous swim bladders retain a connection between the pneumatic duct and the intestinal tract. This allows the fish to fill up the swim bladder by “gulping” air and can remove or expel gas in a similar manner by dumping it into the gut and “burping.” This condition is typical of more primitive bony fishes such as salmon, sturgeon, and herrings. Because physostomes can regulate the air in their body through gulping or burping out air, they may be able to expel air more rapidly in response to sound exposure. This 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.

In contrast, the physoclistous swim bladder is not connected to the intestinal tract via a pneumatic duct. This is considered a closed swim bladder. Thus, physoclist fish regulate gas pressure of the swim bladder through specialized glands. Examples of physoclists can be found among “higher” bony fishes such as perch-like (i.e., Perciformes) fish, tilapia and bass, for example. Fish with closed swim bladders are likely
more sensitive to trauma from exposure to impulsive type sounds such as those produced from pile driving or underwater blasts, since they must moderate the volume of air in the swim bladder through a slow diffusion process (Halvorsen et al., 2012, 2013.).

_Fish without swim bladders_: 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 (e.g., plaice and dab) are capable of detecting and responding to water motion in the near field and acoustic particle motion in the far field (see Sand & Bleckmann, Rogers & Zeddies in Fish Bioacoustics 2008).

_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 spaced to vibrate, generating particle motion that stimulates the inner ear. 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 come in direct contact with the inner ear. (see Fay et al., 2008 in Fish Bioacoustics). 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. The American shad for example, can detect ultrasonic frequencies up to 180 kHz (Mann et al., 1997).

Other species, such as Otophysans (e.g., carps, catfish, and minnows) have a series of specialized small bone structures called Weberian ossicles. The Weberian ossicles are modified bones of the vertebral column that connect the swim bladder to the inner ear, and are thought to facilitate sound transmission and generally improve hearing sensitivity. This enables a higher degree of hearing sensitivity compared to other fish species that lack these structures. Many otophysan fishes can hear frequencies up to 3 kHz or more. For example, goldfish hear up to 4 kHz with best hearing between 500-800Hz.

There are many other fishes that possess swim bladders, but with no special adaptations. These fish 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.

_Lateral Line System_: The lateral line system in fishes is a unique system of tactile sense organs that detects movements and pressure changes in the surrounding water (e.g., water motion). The lateral line possesses the same type of sensory hair cells as those found in fish ears. In general, at frequencies less than 200 Hz, the lateral line is thought to detect particle motion and pressure changes over shorter distances (near field) than the inner ear of fishes (Au & Hastings 2008; Braun& Grand 2008; Webb et al., 2008; Braun & Sand 2014). The lateral line system helps determine the direction and rate of water movement, allowing the fish to orient itself and detect nearby predators or prey, and even water displacement around stationary objects. When considering potential effects from anthropogenic sound exposure, a fish would generally have to be located within close proximity of the sound source, in order to detect particle motion via the lateral line.
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., coral, squid, octopuses and oysters), use sound to obtain information about their environment, and can physically orient themselves based upon the sound characteristics of the areas they occupy. 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. These shrimp can emit noise through the formation of cavitation bubbles, which are produced by striking their enlarged claws. These bubbles produce shockwaves, or “pops” that are capable of stunning prey, or defending the shrimp against predators.

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). 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). The researchers conducted both laboratory and in-field experiments to determine settlement preference in oyster larvae based upon comparisons between oyster reef sound to unstructured soft bottom substrates, which lack the typical oyster reef bed sound. The results of the study suggest that oyster larvae have the ability to respond to sounds indicative of optimal settlement sites, and provide the first evidence that habitat-related differences in estuarine sounds influence the settlement of a mollusk. 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. They recorded and played-back through speakers a compilation of day and night reef sounds to the coral larvae and observed movement of the larvae towards the speakers, independent of chamber
orientation. The study is one of the first descriptions of an auditory response for invertebrates in the phylum Cnidaria (e.g., jellyfish, anemones, hydroids and corals). The researchers suggest that if, like settlement-stage reef fish and crustaceans, coral larvae use reef noise as a cue for orientation and colonisation, 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., 2012; 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 ear 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. 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. 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 seal (Kastak et al., 2008). For a summary of marine mammal noise-induced hearing loss studies, see the NOAA Acoustic Guidance (http://www.nmfs.noaa.gov/pr/acoustics/guidelines.htm).

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

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7 **Impulsive:** sources (transient, brief (less than 1 second), broadband, and typically consist of high peak pressure with rapid rise time and rapid decay (ANSI 1986; NIOSH 1998; ANSI 2005)) vs. **Non-impulsive** sources (can be broadband, narrowband or tonal, brief or prolonged, continuous or intermittent) and typically do not have a high peak pressure with rapid rise time (typically only small fluctuations in dB level) that impulsive signals do (ANSI 1995; NIOSH 1998).
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. 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).

Fish

Physical Effects—Auditory Tissue Damage and Temporary Threshold Shifts: Hearing loss in fishes can occur from exposure to high intensity sounds. These sounds can over-stimulate the auditory system of fishes and may result in temporary threshold shifts (TTS). TTS is considered a non-injurious temporary reduction in hearing sensitivity. Physical injury may also occur for fish exposed to high levels or continuous sound, manifested as a loss of hair cells, located on the epithelium of the inner ear (Hastings & Popper 2005). These hair cells are capable of sustaining injury or damage that may result in a temporary decrease 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 (Lombarte et al., 1993; Smith et al., 2006), unlike mammals. Permanent hearing loss has not been documented in fish.

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. Exposure to loud sounds for a few minutes or hours has been shown to cause TTS in fishes. For example, loss of sensory hair cells due to exposure to sound has been observed in oscars (Astronotus ocellatus), a species of cichlid fish, four days after exposure to 1 hour of 300 Hz continuous tones at 180 underwater dB (Hastings et al., 1996). Similarly, the ears of pink snappers exposed to an operating airgun showed damage, with no evidence of repair or replacement being found 58 days after exposure (McCauley et al., 2003). Scholik and Yan (2001) reported temporary threshold shifts for fathead minnows (Pimephales promelas) exposed to 24 hours of white noise with a bandwidth of 300 – 4000 Hz and overall sound pressure level of only 142 dB (re:1 μPa). Their results indicated that the effects could last longer than 14 days. 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.

Structural damage to the fish inner ear by intense sound has been examined by Enger (1981) and Hastings et al. (1995, 1996) with scanning electron microscopy. As noted above, Hastings et al. (1996) found destruction of sensory cells in the inner ears of oscars four days after being exposed to continuous sound for one hour at 180 dB peak (re:1 μPa) at 300 Hz. Hastings (1995) also reported that 13 out of 34 goldfish exposed for two hours to sound pressure levels ranging from 192 to 204 dB (re:1 μPa) at either 250 or 500 Hz experienced equilibrium problems that included swimming backwards and/or upside down and wobbling from side to side. These fish recovered within one day suggesting that the damage was not permanent. This fish behavior could have been caused by post-traumatic vertigo (lack of balance and dizziness caused by a problem in the inner ear) similar to that experienced by humans after a severe blow to the body or head.

Sound exposure can also affect the lateral line system. A fish would generally have to be located within close proximity of the sound source in order to detect particle motion via the lateral line. As stated previously, the lateral line system in fishes may not necessarily be used for hearing. However, even though fish may not detect and process sound pressure signals via the lateral line as with the auditory system, there is the potential for anthropogenic sound to damage the lateral line, especially from exposure to intense sound. This may affect fish survival if the damage sustained prevented fish from detecting prey or predators for example.

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Physical Effects—Barotrauma: Fish may be injured or killed when exposed to high levels of underwater sound, especially those generated by impulsive sound sources such as pile driving, airguns, or underwater blasts. Pathologies of fish associated with very high sound level exposure and drastic changes in pressure are collectively known as barotraumas. These include hemorrhage and rupture of blood vessels and internal organs, including the swim bladder and kidneys. Death can be instantaneous, occur within minutes after exposure, or occur several days later. Gisiner (1998) reports swim bladders of fish can perforate and hemorrhage when exposed to blast and high-energy impulse noise underwater. If the swim bladder bursts and the air escapes from the body cavity or is forced out of the pneumatic duct, the fish may sink to the bottom. If the swim bladder bursts but the air stays inside the body cavity, the fish is likely to stay afloat but have some difficulty in maneuvering or maintaining position and orientation in the water column. As described above, 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 the rupture of capillaries in the internal organs as indicated by observed blood in the abdominal cavity, and maceration of the kidney tissues, as the internal organs are bound by the vertebral column above and the muscles and skin of the abdominal cavity and cannot move out of the way (Gaspin 1975). Sverdrup et al. (1994) exposed Atlantic salmon to detonating blasting caps, which simulated the blast from a seismic survey. The vascular endothelium showed signs of injury within 30 minutes of exposure, as compared to control specimens that did not show these effects. The fish recovered from their injuries within one week.

Fish can also die when exposed to lower, continuous sound pressure levels if exposed for longer periods of time. Hastings (1995) found death rates of 50 percent and 56 percent for gouramis (Trichogaster sp.) when exposed for two hours or less to continuous sounds at 192 dB rms (re: 1 μPa) at 400 Hz and 198 dB (re: 1 μPa) at 150 Hz, respectively, and 25 percent for goldfish (Carassius auratus) when exposed to sounds of 204 dB (re: 1 μPa) at 250 Hz. Hastings (1995) also reported that acoustic “stunning,” a potentially lethal effect resulting in a physiological shutdown of body functions, immobilized gourami within eight to thirty minutes of exposure to these sound levels.

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 include startle responses and increases in stress hormones. Other potential changes include reduced predator awareness and reduced feeding (Simpson et al., 2014). 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.

Seismic surveys have also been shown to affect the behavior of a number of fish species. These effects include changes in distribution (e.g., Skalski et al., 1992; Engås et al., 1996; Engås & Løkkeborg 2002; Slotte et al., 2004) and other minor behavioral effects such as an initial startle response at the beginning of the exposure that wanes as the airgun shots continue (Wardle et al., 2001; Boeger et al., 2006). Fewtrell and McCauley (2012) found that two species of demersal/pelagic schooling fish demonstrated significant increases in alarm responses to airgun noise exceeding 147 dB SEL, and that alarm responses increased with increasing noise levels, but the responses differed between the two species.

The same Atlantic salmon study conducted by Sverdrup et al. (1994) that resulted in injury to vascular
endothelium from exposure to simulated seismic blasts, also found short-term changes in the levels of stress hormones that were attributed to exposure to the seismic shots. These results are consistent with those of Santulli et al. (1999), who found that European sea bass (*Dicentrarchus labrax*) exposed to airgun blasts also showed short-term (48 hours) variations in several biochemical stress indicators.

Exposure to human-made sound may also result in “agitation” of fishes, indicated by a change in swimming behavior detected by Shin (1995) with salmonids, or “alarm,” detected by Fewtrell (2003). Startle responses may also be exhibited. 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 may not necessarily be injured, but it is exhibiting behavior that suggests it perceives a stimulus indicating potential danger in its immediate environment. However, fish do not exhibit a startle response every time they experience a strong hydroacoustic stimulus.

A study in Puget Sound, Washington, suggests that pile driving operations disrupt juvenile salmon behavior (Feist et al., 1992). Though no underwater sound measurements are available from that study, comparisons between juvenile pink salmon schooling behavior in areas subjected to pile driving/construction and other areas where there was no pile driving/construction indicate that there were fewer schools of fish in the pile driving areas than in the non-pile driving areas. The results are not conclusive but there is a suggestion that pile driving operations may result in a disruption to the normal migratory behavior of the salmon in that study, though the mechanisms salmon may use for avoiding the area are not understood at this time. Feist et al. (1992) also observed that juvenile pink salmon and chum salmon appeared to be less prone to spooking by an observer on the shore when piles were being driven than they were when piles were not being driven. This altered behavior could lead to an increased predation risk.

Vessel noise may also affect fish behavior by causing them to startle, swim away from an occupied area, change swimming direction and speed, or alter schooling behavior (Engas et al., 1995; Mitson & Knudsen 2003; Sand et al., 2008). Some studies have also shown that exposure to continuous or chronic vessel noise may elicit stress responses indicated by increased cortisol levels (Wysocki et al., 2006). More recent research conducted in a busy marine harbor (San Diego Harbor) compared fish stress response to continuous and random intermittent boat noise. Preliminary findings demonstrated increases in cortisol levels were more pronounced in response to intermittent, random boast noise compared to continuous noise (Nichols et al., 2014, unpublished data). These experiments demonstrate physiological and behavioral responses to various boat noises that could affect species fitness and survival.

**Masking:** As discussed above and in Chapter 2, masking generally results from a sound impeding an animal’s ability to hear other sounds of interest. 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. 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.,
However, vocal compensations could have an energetic cost to the individual which may lead to a fitness consequence. This would depend on the balance that is achieved between the energetic cost to the individual and the benefits achieved. For example, reproductive success and survival in species of sciaenids is dependent on the ability of males to successfully attract mates through their vocalizations. Thus, vocal compensation to adjust to changes in ambient noise conditions from vessel noise may increase the ability to successfully attract a mate (Bonacito et al., 2001; Amorin et al., 2002), but conversely may fatigue vocal muscles reducing the number or sound pulses achieved, or increase detection by predators.

**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) showed massive acoustic trauma to squid and octopuses exposed to the high-intensity, low-frequency sounds (50 – 400 Hz) emitted by noise sources such as airguns. 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. This research is some of the first of its kind showing that statocysts provide a form of acoustic detection in cephalopods. Moreover, the research indicates that continuous sound exposure may cause severe acoustic trauma to these species since the damage to the statocysts became more pronounced over time, indicating that exposure to continuous low-frequency ocean noise could cause irreparable damage to the animals by preventing them from carrying out essential life-cycle functions such as hunting, evading predators, or perhaps reproducing.

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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APPENDIX A

DRAFT OCEAN NOISE STRATEGY ROADMAP


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