# APPENDIX J

# FISH HEARING AND SENSITIVITY TO ACOUSTIC IMPACTS

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# 1. INTRODUCTION

This report considers the effects of human-generated (anthropogenic) sound on fishes, with particular reference to seismic airguns and sonars. However, since there are few data on the effects of any anthropogenic sources on fishes, much of the discussion will be based upon a wider range of sound sources, with a goal of some extrapolation to help inform potential effects from airguns and sonars. Emphasis will be placed upon peer-reviewed studies in the scientific literature. However, gray literature reports of high scientific quality will be cited as appropriate.

It should be noted that this review will not be comprehensive. Readers interested in more extensive analysis of the effects of anthropogenic sounds on animals are referred to Popper (2003), Hastings (2008), Popper and Hastings (2009a), and Slabbekoorn et al. (2010) for general reviews and to Popper and Hastings (2009b) and the papers in Popper and Hawkins (2011) for a more detailed overview.

## 1.1. WHAT IS INJURY FOR FISHES?

A fundamental issue of concern with regard to fishes is what constitutes "injury" in the sense of the marine mammal literature (see Southall et al. [2007]) and the Marine Mammal Protection Act. For marine mammals, permanent hearing loss (or permanent threshold shift [PTS]) is considered injury. But, as discussed below, PTS is not likely to occur in fishes, and all evidence for temporary hearing loss (or temporary threshold shift [TTS]) shows that fishes recover quickly from this loss. Thus, for the sake of this discussion, "injury" would not include effects on hearing.

So, a question of importance is when "injury" starts in fishes and the nature of physiological effects that can lead to injury. In the very limited literature on interim criteria for regulation of exposure of fishes to pile driving sound (regulations have not be promulgated for other sound sources), the concern is for the onset of physiological effects, but this is not clearly defined. In a recent study by Halvorsen et al. (2011a,b) on effects of pile driving sounds on Chinook salmon (and similar studies by Casper et al., 2011a on striped bass and tilapia), it has become clear that there are some effects that have the potential for impacting the survival of fishes (e.g., burst swim bladder, massive internal bleeding), whereas other effects have no more impact on survival than does a small cut on the arm of a human (e.g., external bleeding at the base of fins).

Therefore, until a better definition of "injury" is available and agreed upon for fishes, an injury will be defined as an effect on the physiology of the animal that leads to immediate or potential death for the purposes of this report. In contrast, behavioral effects, such as moving from a site of feeding, would not be considered an injury.

At the same time, it might ultimately be possible and worthwhile to attempt to define criteria for behavioral impacts. However, as discussed in the body of this report, there are no data currently available that provide guidance on this topic.

## 1.2. FISH

The term "fish" generally refers to three groups of vertebrates: (a) the Agnatha or jawless vertebrates; (b) the cartilaginous fishes; and (c) the bony fishes (see Nelson [2006]). The Agnatha are a small group of very ancient vertebrates that primarily includes lamprey, and they will not be considered further. See Nelson (2006) for a complete review of fishes and their evolutionary relationships and www.fishbase.org for a listing of the more than 32,000 known living species.

The cartilaginous fishes, or elasmobranchs, include sharks and rays and their relatives. Virtually nothing is known about effects of human-generated sound on cartilaginous fishes, but there is concern about potential effects since these animals are integral to the ecosystem in many parts of the marine environment (Casper et al., 2011b).

Bony fishes include most of the species of aquatic vertebrates, including the majority of the species of fishes that are consumed by humans[1]. Unless otherwise stated, the term "fishes" in this report will refer to bony fishes. By convention, the word "fish" refers to one or more members of the same species, whereas "fishes" refers to multiple species.

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[1] E.g., tuna, salmon, cod, herring, pollack, and many others.

## 1.3. FISH BIOACOUSTICS – OVERVIEW

Sound plays a major role in the lives of all fishes (e.g., Zelick et al., 1999; Fay and Popper, 2000). This is particularly the case since sound travels much further in water than other potential signals, and it is not impeded by darkness, currents, or obstacles in the environment. Thus, fishes can glean a great deal of information about biotic (living) and abiotic (environmental) sources and get a good "image" of the environment to a very substantial distance from the animal (e.g., Fay and Popper, 2000; Popper et al., 2003; Slabbekoorn et al., 2010).

In addition to listening to the overall environment and being able to detect sounds of biological relevance (e.g., the presence of a reef, the sounds produced by swimming predators), many species of bony fishes (but not elasmobranchs) communicate with sounds and use sounds in a wide range of behaviors including, but not limited to, mating and territorial interactions (see Zelick et al. [1999] for review). Consequently, anything that impedes the ability of a fishes to hear biologically relevant sounds, such as those produced by anthropogenic sound sources, could interfere with the normal behaviors and even the survival of individuals, populations, or a species. Much more detailed discussions of all aspects of fish bioacoustics can be found in the papers in Webb et al. (2008) and in papers by Fay and Megela-Simmons (1999), Zelick et al. (1999), and Popper et al. (2003). A broad discussion of interactions of anthropogenic sounds and fishes can be found in Popper and Hastings (2009a,b) and in the papers in Popper and Hawkins (2011).

## 1.4. METRICS OF SOUND EXPOSURE

Before discussing effects of anthropogenic sound on fishes, it is important to understand that, to date, it has not been possible to easily compare results from the studies with different anthropogenic sources. In part, this is because while different sources are reasonably similar in maximum intensity, they have different spectral characteristics and rise times. In particular, rise time, which is the time from the onset of the signal to when it reaches a high level, can impact effects. Signals with slow rise times will affect air bubbles in the body (e.g., swim bladder) slowly, and so the bubbles will change size slowly and let the surrounding tissues adjust to the changes. In contrast, a signal with a fast rise time will cause rapid changes of the air bubbles, and the walls of the expanding and contracting bubble will "knock into" the surrounding tissues, which are, in effect, rigid next to the moving bubble. This causes damage to the nearby tissues. An analogy might be the effect on a nail being pounded through hard wood by a weak versus strong hammer strike.

The second issue in comparing results arises from the spectrum and time course of the signal and how these are described and calibrated. Until recently, most sound sources were described in terms of peak pressure and root-mean-square (rms) pressure. Peak pressure represents the maximum point of the energy in a signal whereas rms describes the average level of energy in the signal. The problem with both measures is that they do not give a good representation of the total energy in the signal over time – and it is this total energy that is likely to be the critical factor in determining potential effects on a receiver (Popper and Hastings, 2009b).

In comparing sounds such as sonars, seismic airguns, and pile driving, there may be similarities in both peak and rms, but neither measure shows the actual differences in the total energy to which a receiver is exposed. More recently, investigators have started to use a third measure, the Sound Exposure Level (SEL). The SEL is the integration over time of the square of the acoustic pressure (Popper and Hastings, 2009b) and is an indication of the total acoustic energy received by an organism, representing the total energy in a signal over time – most often in one second of exposure (see Popper and Hastings [2009b] for discussion of SEL and how it is calculated). SEL allows for a comparison between signals since it provides a measure of all energy present in a signal, and it has, accordingly, been more and more accepted by investigators (e.g., Popper et al., 2005, 2007; Hastings et al., 2008; Hastings and Miskis-Olds, 2011; Halvorsen et al., 2011a,b).

There are two uses of SEL. One is referred to as single-strike SEL ($SEL_{ss}$), and the other is cumulative SEL ($SEL_{cum}$)[2]. The $SEL_{ss}$ is the energy in a single signal, such as a single pile driving strike

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[2] Note, abbreviations for single strike and cumulative SEL has not been standardized and is adopted here from Halvorsen et al. (2011b).

or a single blast from a seismic airgun. The $SEL_{cum}$ is the energy in all of the signals presented, such as in all of the strikes during a pile driving operation or seismic study[3].

# 2. BACKGROUND ON FISH HEARING

## 2.1. SOUND IN WATER

The basic physical principles of sound in water are the same as sound in air. Any sound source produces both pressure waves and actual motion of the medium particles. However, whereas the actual particle motion in air is inconsequential even a few centimeters from a sound source, particle motion travels (propagates) much further in water because of the density of water compared to air[4]. For a more extensive discussion of underwater acoustics, see Urick (1983) and Rogers and Cox (1988).

All fishes, including elasmobranchs, detect particle motion since it directly stimulates the inner ear (Popper et al., 2003). Bony fishes with an air bubble (most often the swim bladder) are also likely to detect pressure signals that are reradiated to the inner ear as particle motion. Species detecting pressure hear a wider range of frequencies and sounds of lower intensity than fishes without an air bubble since the bubble re-radiates the received signal, which is then detectable by the ear as a secondary sound source (Popper et al., 2003; Popper and Fay, 2010).

Exactly how well fishes with an air bubble hear depends on the relative position of the air bubble and ear. When the two structures are close together or when there is some kind of physical coupling between them the bandwidth of hearing and sensitivity is greater than it is in fishes where the air bubble and ear are further apart or not coupled. In the latter case, the signal that is re-radiated from the air bubble attenuates (decreases) over the distance between the structures, whereas in the other species the proximity of the structures, or the coupling, ensures that most of the energy re-radiated from the bubble gets to the ear[5].

## 2.2. HEARING SENSITIVITY

Basic data on hearing provides information about the range of frequencies that a fish can detect and the lowest sound level that an animal is able to detect at a particular frequency (**Figure J-1**). This level is often called the "threshold."[6] Sounds that are above threshold are detectable by fishes.

Hearing thresholds have been determined for perhaps 100 species (**Figure J-1**) (for data on hearing thresholds, see Fay [1988], Popper et al. [2003], Ladich and Popper [2004], Nedwell et al. [2004], Ramcharitar et al. [2006], and Popper and Schilt [2008]). These data demonstrate that, with few exceptions, fishes cannot hear sounds above about 3-4 kHz, and the majority of species are only able to detect sounds to 1 kHz or below[7]. There have also been studies on a few species of cartilaginous fishes, with results suggesting that they detect sounds to no more than 600 or 800 Hz (e.g., Myrberg et al., 1976; Myrberg, 2001; Casper et al., 2003; Casper and Mann, 2006).

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[3] As discussed below, there is some indication that if there is sufficient time (e.g., more than 12 hrs) between an accumulation period for SEL, then the accumulation for the next exposure period starts again at 0.

[4] The wavelength of a sound in water is about 1,500 m/sec (it varies depending on salinity, depth, temperature, etc.). The wavelength is defined as 1500/frequency which means for a 500 Hz signal the wavelength is 3 m. For a 100 Hz signal the wavelength is 15 m and the near field transition point would be 15/6.28 = ~2.8 m.

[5] Until recently the literature talked about hearing "generalists" and "specialists." However, these terms are no longer in use. See Popper and Fay (2010) for explanation and discussion.

[6] Very often, for fish, hearing thresholds are the lowest levels at which sound is detected 50% of the time. In other words, whereas a fish will detect a particular signal 50% of the time, it will not detect the same signal 50% of the time. Variation in threshold is well known and reflects momentary changes in the detecting structure, in the motivation of the animal, and innumerable other factors.

[7] The lowest detectable frequency is often hard to determine since the limiting factor in experiments trying to measure this is often the equipment. In many cases, the equipment does not work well at frequencies below 50-100 Hz, making it hard to determine if fishes can detect lower frequencies. However, recent studies using specialized equipment have demonstrated that some species can detect sounds below 50 Hz (called infrasound), but it is still not clear if this is done by the ear or by the lateral line (Karlsen, 1992; Knudsen et al., 1994).

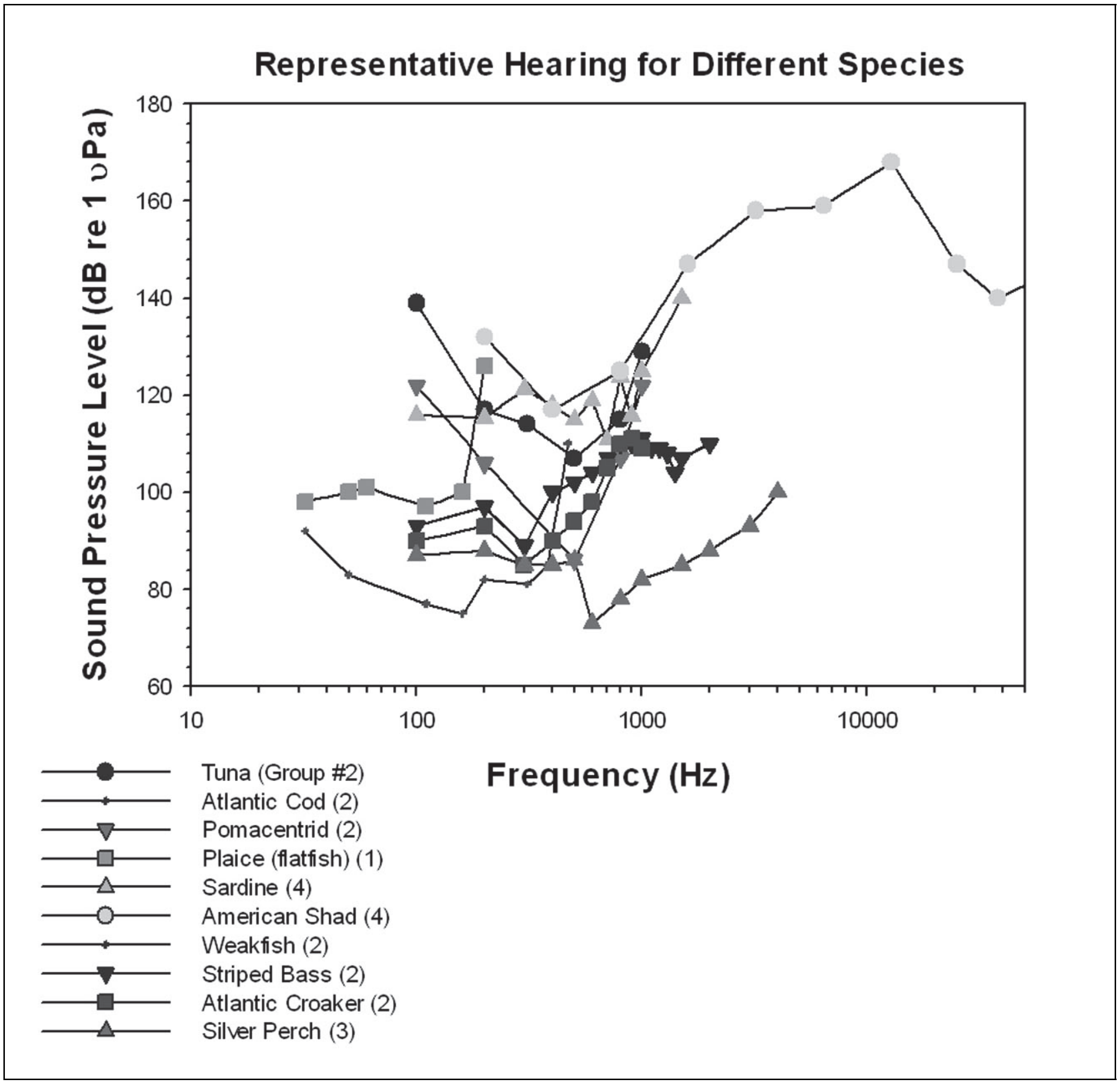

Figure J-1. Hearing Curves (Audiograms) for Select Bony Fishes (see Fay [1988], Nedwell et al. [2004], and Ramcharitar [2006] for data). Each data point indicates the lowest sound level the species could detect at a particular frequency (see text for caveats on data). Group number given in the legend refers to the discussion within the text. Data for American shad are truncated at 50 kHz to keep the size of the graph reasonable, but it should be noted that this species can hear sounds to at least 180 kHz (Mann et al., 1997).

The data available, while very limited, suggest that the majority of marine species do not have specializations to enhance hearing and probably rely on both particle motion and sound pressure for hearing. Most importantly, it should be noted that hearing capabilities vary considerably between different bony fish species (**Figure J-1**; **Table J-1**), and there is no clear correlation between hearing capability and environment. There is also broad variability in hearing capabilities within a single fish group. As just one example, there is broad diversity in hearing capabilities and hearing structures within the family Sciaenidae (drumfish, weakfish, croakers) (**Figure J-1**; data reviewed in Ramcharitar et al. [2006]; see also Popper and Schilt [2008]).

Table J-1

Marine Fish Hearing Sensitivity

| Family | Common Name of Taxa | Highest Frequency Detected (Hz)[a] | Hearing Category[b] | Reference | Notes |
|---|---|---|---|---|---|
| Asceripensidae | Sturgeon | 800 | 2 | Lovell, et al., 2005; Meyer et al., 2010 | Several different species tested. Relatively poor sensitivity |
| Anguillidae | Eels | 300 | 2 | Jerkø et al., 1989 | Poor sensitivity |
| Batrachoididae | Toadfishes | 400 | 2 | Fish and Offutt, 1972; Vasconcelos and Ladich, 2008 | |
| Clupeidae | Shad, menhden | >120,000 | 4 | Mann et al., 1997, 2001 | Ultrasound detecting, but sensitivity relatively poor |
| | Anchovy, sardines, herrings | 4,000 | 4 | Mann et al., 2001 | Not detect ultrasound, and relativley poor sensitivitiy |
| Chondrichthyes [Class] | Rays, sharks, skates | 1,000 | 1 | Casper et al., 2003 | Low-frequency hearing, not very sensitive to sound |
| Gadidae | Atlantic cod, haddock, pollack, hake | 500 | 2 | Chapman and Hawkins, 1973; Sand and Karlsen, 1986 | Probably detect infrasound (below 40 Hz).<br>Best hearing 100-300 Hz |
| | Grenadiers | | 3? | Deng et al., 2011 | Deep sea, highly specialized ear structures suggesting good hearing, but no measures of hearing |
| Gobidae | Gobies | 400 | 1 or 2 | Lu and Xu, 2009 | |
| Labridae | Wrasses | 1,300 | 2 | Tavolga and Wodinksy, 1963 | |
| Lutjanidae | Snappers | 1,000 | 2 | Tavolga and Wodinksy, 1963 | |
| Malacanthidae | Tilefish | | 2 | NA | No data |
| Moronidae | Striped bass | 1,000 | 2 | Ramcharitar unpublished | |
| Pomacentridae | Damselfish | 1,500 – 2,000 | 2 | Myrberg and Spires, 1980 | |
| Pomadasyidae | Grunts | 1,000 | 2 | Tavolga and Wodinsky, 1963 | |
| Polyprionidae | Wreckfish | | 2 | NA | No data |
| Sciaenidae | Drums, weakfish, croakers | 1,000 | 2 | Ramcharitar et al., 2006 | Hear poorly |
| | Silver perch | 3,000 | 3 | Ramcharitar et al., 2004, 2006 | |
| Serranidae | Groupers | | 2 | NA | No data |
| Scombridae | Yellowfin tuna | 1,100 | 2 | Iversen, 1967 | With swim bladder |
| | Tuna | 1,000 | 1 | Iversen, 1969 | Without swim bladder |
| | Bluefin tuna | 1,000 | 2 | Song et al., 2006 | Based only on ear anatomy |

[a] Lower frequency of hearing is not given since, in most studies, the lower end of the hearing bandwidth is more a function of the equipment used than determination of actual lowest hearing threshold. In all cases, fish hear below 100 Hz, and there are some species studied, such as Atlantic cod, Atlantic salmon, and plaice, where fish have been shown to detect infrasound, or sounds below 40 Hz.

[b] See text for explanation.

Notes: See text for important caveats about the data. For a number of additional species, hearing capabilities can only be surmised from morphological data. These data are shown shaded in gray

Sources: Data compiled from reviews in Fay (1988) and Nedwell et al. (2004). Updated names: www.fishbase.org.

**Table J-1** and **Figure J-1** provide data on a number of fish groups of potential interest for this report. The data in **Table J-1** are presented in terms of fish taxa (family level) since data are often not available for specific species of interest. However, it is possible to extrapolate between broad groups of fishes in most cases. Where that is not the case, as in the sciaenids (reviewed in Ramcharitar et al., 2006), several different sets of data are shown. Moreover, this is also done when species within a group differ substantially in hearing structures. Thus, in the case of tuna, there are some species with a swim bladder (involved in pressure detection) and others that do not have a swim bladder (Iversen, 1967, 1969). Indeed, in the case of tuna, while the hearing range of the species with and without swim bladders is quite similar, it is likely that the sensitivity is poorer in the species without this structure.

It should also be noted that **Table J-1** only gives the likely highest frequency of hearing for a fish and leaves out the low frequency end of the hearing bandwidth. This is done because what is known about low frequency hearing is often a function of the equipment used in the study and not what the fish actually hears. Thus, if the sound source used to study hearing is only good to 100 Hz, then that might be the lowest frequency that investigators report. As a consequence, the low frequency range, with a few exceptions, must be viewed with caution, even as presented in **Figure J-1**. However, it is accurate to state that most, if not all, fishes can detect sounds to below 100 Hz and likely to below 50 Hz.

Another point to note is that **Table J-1** does not show hearing sensitivity, and the data in **Figure J-1** are not presented as thresholds but as relative levels of hearing within a single fish's hearing capabilities. Thus, **Table J-1** does not show the lowest sound levels that a fish can hear, nor does it indicate at what frequency best hearing occurs. The table is presented as it is because there is wide variation in data even for a single species (e.g., see Fay [1988] for a demonstration of different data on hearing for goldfish). The variation is likely a result of experimental design. It is often the case that the investigators did not use the right stimulus parameter (pressure or particle motion) to test a species. Thus, investigators have often presented hearing sensitivity data for fishes in terms of pressure sensitivity, even when the fish is likely not to detect sound pressure as it primarily detects particle motion (something that, until recently, has been very hard to measure).

With these caveats, it is possible to make some useful generalizations with regard to fish hearing that remove some of the "variability" in the data and help focus understanding of fish hearing capabilities. Such generalizations also make it possible to "predict" hearing range and sensitivity of some species for which there are data on the structure of the ear and auditory system but no hearing data. Indeed, such is the case for bluefin tuna, where, despite lack of hearing data, it is possible to predict that the hearing range for this species is similar to that of other tuna based on similarities in ear structure (Song et al., 2006). Similarly, morphological data on the ears of deep-sea grenadiers leads to the suggestion that these species have inner ear specializations that are often associated with fishes that hear to 2,500-4,000 Hz and have good hearing sensitivity (Deng et al., 2011); a similar observation has been made for myctophids (Popper, 1980).

Based on this kind of analysis, it is possible to "categorize" fish groups as to their hearing capabilities. This is presented in **Table J-1** where a column provides the categories of each species represented, which are defined as follows:

- *Group 1*: Fishes that do not have a swim bladder (e.g., Plaice in **Figure J-1**). These fishes are likely to use only particle motion for sound detection. The highest frequency of hearing is likely to be no greater than 400 Hz, with poor sensitivity compared to fishes with a swim bladder. Fishes within this group would include flatfish, some gobies, some tunas, and all sharks and rays (and relatives).
- *Group 2*: Fishes that detect sounds from below 50 Hz to perhaps 800-1,000 Hz (though several probably only detect sounds to 600-800 Hz). These fishes have a swim bladder but no known structures in the auditory system that would enhance hearing, and sensitivity (lowest sound detectable at any frequency) is not very great. Sounds would have to be more intense to be detected when compared to fishes in Group 3. These species detect both particle motion and pressure, and the differences between species are related to how well the species can use the pressure signal. A wide range of species fall into this category, including tuna with swim bladders, sturgeons, salmonids, etc.

- *Group 3*: Fishes that have some kind of structure that mechanically couples the inner ear to the swim bladder (or other gas bubble), thereby resulting in detection of a wider bandwidth of sounds and lower intensities than fishes in other groups (e.g., silver perch in **Figure J-1**). These fishes detect sounds to 3,000 Hz or more, and their hearing sensitivity, which is pressure driven, is better than in fishes of Groups 1 and 2. There are not many marine species known to fit within Group 3, but this group may include some species of sciaenids (Ramcharitar et al., 2006). It is also possible that a number of deep-sea species fall within this category, but that is only predicted based on morphology of the auditory system (e.g., Popper, 1980; Deng et al., 2011). Other members of this group would include all of the Otophysan fishes, though few of these species other than catfishes are found in marine waters.
- *Group 4*: All of these fishes are members of the herring family and relatives (Clupeiformes). Their hearing below 1,000 Hz is generally similar to fishes in Group 1, but their hearing range extends to at least 4,000 Hz (e.g., sardine in **Figure J-1**), and some species (e.g., American shad) are able to detect sounds to over 180 kHz (Mann et al., 2001).

## 2.3. OTHER ASPECTS OF FISH HEARING

Besides being able to detect sounds, a critical role for hearing is to be able to discriminate between different sounds (e.g., frequency and intensity), detect biologically relevant sounds in the presence of background noises (called maskers, see below), and determine the direction and location of a sound source in the space around the animal. While actual data are available on these tasks for only a few fish species, all species are likely to have similar capabilities (reviewed in Fay and Megela-Simmons, 1999; Popper et al., 2003; Fay, 2005).

Only a few points about the hearing structure in fishes is critical for this report, and readers interested in more detail can find reviews by Popper et al. (2003) and Popper and Schilt (2008). The fundamental structure for hearing by fishes is the inner ear. This is, in many ways, very similar in structure and function to the ear found in all other vertebrates. The inner ear has three otolith organs – the saccule, lagena, and utricle – each containing a dense structure called an otolith. The otolith lies in close proximity to a sensory surface called the sensory epithelium. Each epithelium contains sensory hair cells that are very similar to those found in the mammalian ear. On their top surfaces, sensory hair cells have hair-like projections, called cilia, that are bent when the epithelium and otolith move out of phase from one another – something that takes place when sound stimulates the ear. The sensory cells respond physiologically to the bending of the cilia and send signals on to the brain via the eighth cranial nerve – the same nerve involved in hearing in humans.

Germane to issues of effects of loud sounds on fishes is that the sensory hair cells in fishes, as in mammals (including humans), can be damaged or actually killed by exposure to very loud sounds (Le Prell et al., 2011). However, whereas in humans once sensory cells die they are not replaced, resulting in deafness, fishes are able to repair and replace cells that die (e.g., Lombarte et al., 1993; Smith et al., 2006). Moreover, whereas in humans the ear has its full complement of sensory hair cells at birth, fishes continue to produce (proliferate) sensory hair cells for much of their lives, which results in fishes having more and more sensory hair cells as they age (Popper and Hoxter, 1984; Lombarte and Popper, 1994). Indeed, large Mediterranean hake (*Merluccius merluccius*) have been shown to have a million or more sensory hair cells in a single saccule (Lombarte and Popper, 1994), as compared to humans which have, at birth, no more than 20,000 sensory cells in the auditory part of the ear.

Because fishes have the ability to repair damaged sensory hair cells and continuously add to their number, fishes are not likely to ever become deaf permanently. As discussed below, there is some chance of temporary hearing loss, but this is quickly repaired (Smith et al., 2006), and there is no evidence in fishes for permanent hearing loss.

# 3. EFFECTS OF HUMAN-GENERATED SOUND ON FISHES – OVERVIEW

There is a wide range of potential outcomes of exposing fishes to sound, from no effect to immediate death. Data on effects of sounds are limited, and broad extrapolations about effects on different species (or on the same species at different ages or sizes) is not yet possible (see discussion in Popper and Hastings [2009b] and Popper and Hawkins [2011]). Moreover, while there are some (albeit limited) data on effects on physiology, far less is known about effects on behavior.

The actual effects will vary based on a large number of factors. In particular, other than for physiological damage, which does not depend on hearing per se, the likelihood of TTS, masking, and/or behavioral change will depend on whether the fish hears the sound. **Figure J-2** illustrates the idea that there is a likelihood of any number of different potential effects close to the source and that the range of potential effects declines with increased distance from the source.

The actual effects are also likely to depend on the nature of the sound source itself. One may divide sounds into two very overlapping "classes": intermittent (or acute) and long-term (or chronic) (Popper and Løkkeborg, 2008). Intermittent sounds usually are of short duration and high intensity, and they are only present in a particular area for a short period of time. These include sounds produced by seismic airguns, sonars, and similar sources. Pile driving would also fit into this category, although it may last for hours, days, or even weeks. But, ultimately, pile driving ends. Loud intermittent sounds have the potential to cause death and physiological effects if the animal is close to the source. They could also produce hearing loss, masking, and behavioral effects to distances beyond those that would result in death or damage (**Figure J-2**).

Long-term (chronic) sources are generally lower in intensity than acute signals, may extend over a broad area, and, in general, raise the ambient noise level from a few to many decibels. In essence, chronic noise sources raise the overall background ambient level of the environment similar to what might be encountered when new machinery is added to a factory. In the case of the aquatic environment, perhaps the most dominant changes in the chronic noise environment come from boats which, is more likely to occur in a harbor, major shipping lanes, and similar areas. Long-term rises in sound level are not likely to result in death or physiological effects (though it is possible that there may be long-term changes in stress levels and immune response), but they could also produce hearing loss, masking, and/or behavioral effects (**Figure J-2**).

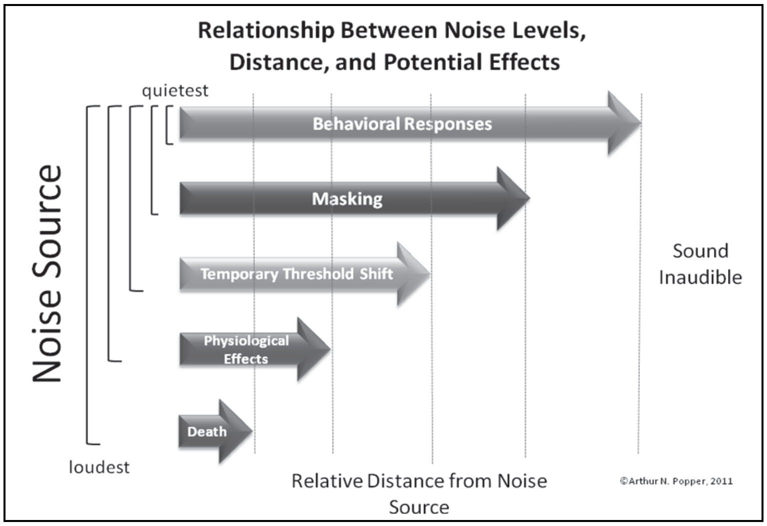

Figure J-2. Relationship between Noise Levels, Distance, and Potential Effects. (Note that close to the source, there is a range of potential effects, but as the distance from the source increases and sound levels get lower, the likelihood of some potential effects decreases. The actual effects will vary depending on the source. If the source is very intensive, then mortality may occur. But, if the source is less intensive, mortality and physiological effects may mot be an issue. At the lowest source levels, such as with increases in ambient sounds, behavioral responses and/or masking may be the only issues of concern.)

# 4. EFFECTS OF ANTHROPOGENIC SOUNDS ON HEARING

While there are few data on behavioral effects of sounds on fishes in the wild (**Section 6.0**), there are substantial data on effects of such sounds on the ability of fishes to hear. If hearing is impaired, even temporarily, a fish may not be able to find food or detect predators as successfully. Such impairment may be by auditory masking or temporary loss of hearing.

## 4.1. AUDITORY MASKING

Masking is a key issue for potential effects of human-generated sound on all vertebrates, including fishes (reviewed in Fay and Megela-Simmons, 1999; Popper et al., 2003). Masking occurs when there are sounds in the environment that are in the same frequency range as the sound of biological relevance to the animal and/or within the hearing range of the fishes. Thus, if a fish has a particular threshold for a biologically relevant sound in a quiet environment and a background noise in the same frequency range is introduced, this will decrease the ability of the fish to detect the biologically relevant signal. In effect, the threshold for the biologically relevant signal will become poorer. Thus, if background noise increases, it may be harder for a fish to detect the biologically relevant sounds that it needs to survive. Specifically, if the ambient noise (or masker) is raised by 10 dB, the threshold of the fish will increase by about 10 dB in the frequency range of the masker.

The actual concern with regard to masking is that fishes will not be able to hear sounds of biological relevance as well as they would without the masking sound. Thus, if a fish uses sounds to detect predators, the presence of the increased ambient sound would keep the fish from hearing the predator until it was much closer. Similarly, if male fishes use sounds to attract females, as occurs in toadfish (reviewed in Zelick et al., 1999), sciaenids (reviewed in Ramcharitar et al., 2006), and many other species, the female would have to be much closer to the males before they could hear the sound. In other words, the effectiveness of a male's call would decline in the presence of masking sounds since the females would be less likely to detect the sounds unless they are closer to the source (where the source is louder in the presence of the masker). Indeed, this effect is well known and has been described for a wide range of other vertebrates, including birds and amphibians (reviewed in Slabbekoorn et al., 2010).

More recently, it has been suggested that at least some larval fishes find the reefs upon which they will settle using sounds from the reef (e.g., Leis et al., 2003; Wright et al., 2005). These studies have suggested that if there is an increase in ambient (masking) noise, the larval fish would be less likely to hear the sounds of the reef and, thus, less likely find a place to settle. The reef sounds could be produced by a variety of sources, including snapping shrimp, water moving over reefs, other fishes, etc. and would be subject to masking by anthropogenic sounds within the hearing range of fishes. Clearly, if this observation is correct, then the presence of masking sounds could have a significant impact on long-term survival of populations of reef fishes.

## 4.2. TEMPORARY THRESHOLD SHIFT

A second concern is that exposure to sounds can result in a temporary loss of hearing sensitivity, or TTS. Temporary threshold shift recovers after some period of time following the termination of the noise and results from temporary, but recoverable, damage to the sensory cells of the inner ear that are involved with for hearing (Smith et al., 2006). Permanent hearing loss (i.e., PTS), resulting from exposure to very loud sounds, occurs in humans and other mammals. Permanent threshold shift is not, however, known to occur in fishes, since unlike mammals, they can repair and regenerate the sensory cells of the ear that are damaged (e.g., Lombarte et al., 1993; Smith et al., 2006)[8].

Data on TTS in fishes are reviewed in Popper and Hastings (2009b) and are only briefly summarized here. The data suggest that TTS occurs after long-term exposure to sounds that are as high as 170-180 dB re 1 µPa (rms), but only in species that have specializations that result in their having relatively wide hearing bandwidths (to over 2 kHz) and lower hearing thresholds than fishes without specializations. For example, TTS of 10-20 dB has been demonstrated in goldfish (*Carassius auratus*) and lined Raphael catfish (*Platydoras costatus*) (e.g., Scholik and Yan, 2002; Smith et al., 2004a, 2006;

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[8] Interesting, the sensory cells in the mammalian and fish ear responsible for hearing are the same. The difference between fishes and mammals is that fishes retain a regenerative mechanism in the ear for when cells are lost, whereas no such capacity is found in mammals.

Wysocki and Ladich, 2005), but little or no TTS has been found in fishes such as cichlids, sunfishes, and perch (e.g., Scholik and Yan, 2001; Amoser and Ladich, 2003; Smith et al., 2004a,b; Wysocki and Ladich, 2005). Moreover, studies of the effects of exposure to 150 dB re 1 µPa (rms, received level) for 9 months showed no effect on hearing or on survival and growth of young rainbow trout (*Oncorhynchus mykiss*) (Wysocki et al., 2007). Significantly, in those species where TTS was found, hearing returned to normal starting well within 24 hrs after the end of exposure (e.g., Smith et al., 2004b, 2006).

While TTS is not as likely to be particularly irrelevant with regard to repetitive sound sources, concerns have still arisen that fishes may temporarily have impaired hearing as a result of exposure to loud sounds (e.g., Popper et al., 2005, 2007; reviewed in Popper and Hastings, 2009b). Several studies show varying results, but overall, if TTS occurs as a result of exposure to loud sounds, it is not necessarily very great and recovery seems to be within 24 hrs in most cases (Popper et al., 2005, 2007; Hastings et al., 2008; Hastings and Miskis-Olds, 2011).

The potential effects of TTS are similar to those of masking (**Section 4.1**). If the hearing ability of an affected fish decreases, then the likelihood of detecting predators, prey, or mates (or a reef) decline, thus decreasing the potential fitness of the receiver until normal hearing returns.

## 4.3. EFFECTS OF HIGH INTENSITY SOURCES ON HEARING

Several studies have examined the effects of very high intensity sources on hearing and demonstrate little or no effect on a diverse group of species. Popper et al. (2005) and Song et al. (2008) examined the effects of exposure to a seismic airgun array on three species of fishes found in the Mackenzie River Delta near Inuvik, Northwest Territories, Canada. One species, the lake chub (*Couesius plumbeus*), has hearing specializations, whereas the northern pike (*Esox lucius*) and the broad whitefish (*Coregonus nasus*) (a salmonid) do not. Fishes were exposed to 5 or 20 shots from a 730-in$^3$ (12,000 cc) calibrated airgun array. And unlike earlier studies, the received exposure levels were not only determined for rms sound pressure level, but also for peak sound levels and SELs (e.g., average mean peak SPL 207 dB re 1 µPa RL; mean rms sound level 197 dB e 1 µPa RL; mean SEL 177 dB re 1 µPa$^2$s).

For both the 5 and 20 airgun shots, the results showed a temporary hearing loss for both lake chub and northern pike but not for broad whitefish. Hearing loss was on the order of 20-25 dB at some frequencies for both the northern pike and lake chub; full hearing recovery occurred within 18 hrs after sound exposure.

Popper et al. (2007) studied the effect of the Surveillance Towed Array Sensor System (SURTASS) low-frequency active (LFA) sonar on hearing, the structure of the ear, and select non-auditory systems in the rainbow trout and channel catfish (*Ictalurus punctatus*) (also Halvorsen et al., 2006). Fishes were exposed to LFA sonar for 324 or 648 seconds, an exposure duration that is far greater than any fishes in the wild would get since, in the wild, the sound source is on a vessel moving past the far slower swimming fishes. The maximum received level was approximately 193 dB re 1 µPa at 196 Hz. Analysis of hearing showed that channel catfish and some specimens of rainbow trout showed 10-20 dB of hearing loss immediately after exposure to the LFA sonar when compared to baseline and control animals; however, another group of rainbow trout showed no hearing loss. Recovery in trout took at least 48 hrs, and channel catfish recovered with 24 hrs. Similar studies on several other species, including hybrid sunfish and black perch, showed no TTS to the same signals (Halvorsen et al., 2006).

Finally, Hastings et al. (2008) studied TTS in Indian Ocean reef fishes during a seismic survey with a full airgun array. They found no hearing loss following sound exposures up to 190 dB re 1 µPa$^2$-s cumulative SEL in a species that hears well, in the pinecone soldierfish (*Myripristis murdjan*), and in three species that do not have hearing specializations: the blue green damselfish (*Chromis viridis*), sabre squirrelfish (*Sargocentron spiniferum*), and bluestripe seaperch (*Lutjanus kasmira*).

In summary, it is clear that if hearing loss occurs after exposure to intense sounds (and it does not always occur), it primarily shows up in fishes with hearing specializations and is not permanent (i.e., there is full recovery). More importantly, TTS is less likely to show up in fishes without hearing specializations. The only time that TTS has been documented as a response to high intensity sources has been when the exposure duration has substantially exceeded the amount of time that an animal would normally be exposed to such sounds in the wild (Popper et al., 2007).

# 5. EFFECTS OF HIGH INTENSITY SOURCES

Intensive sources are generally short (measured in parts of a second to several seconds) and are highly intensive at the source (attenuation follows normal attenuation characteristics of sound in water). Also, exposure time to the sound for an animal may be rather short. For example, a fish exposed to high intensity sonar may only hear a few sonar sounds since the source, on a boat, is moving. In the case of seismic devices, the source is constantly moving, although the sounds may increase the overall ambient noise for the duration of a 3D seismic study. Sounds from pile driving may last for as long as the pile driving operation, but there frequently are periods of pile driving followed by longer periods of silence as new piles are added, hammers moved or repaired, etc.

The concerns associated with intensive sources range from immediate mortality to delayed mortality to behavioral effects (**Figure J-2**). Behavioral effects are varied and less likely to involve masking or TTS, as found in long-term exposures, because of the short periods of the intense sounds. However, there are concerns, as discussed below, that an extended seismic survey could result in fishes leaving their feeding or spawning areas for extended periods of time, or even permanently, which could impact survival of populations as well as catchability for fishers (e.g., Engås et al., 1996; Slotte et al., 2004; Løkkeborg et al., 2011).

At the same time, while much concern about intensive sources rests on immediate mortality, the limited data suggest that the circumstances under which immediate mortality occurs are very limited. Indeed, there are no data to suggest mortality associated with high intensity sources other than pile driving[9].

The only data on mortality associated with sound (as compared to explosives) come from driving very large piles. For example, the California Department of Transportation (Caltrans, 2001) showed some mortality for several different species of wild fishes exposed to driving of steel pipe piles 2.4 m (8 ft) in diameter. However, no mortality seems to occur at distances of more than approximately 10 m (32.8 ft) from the source.

## 5.1. NON-AUDITORY PHYSIOLOGICAL EFFECTS OF EXPOSURE TO INTENSE SOUNDS

Non-auditory physiological effects from exposure to intense sounds generally result from rapid and substantial expansion and contraction of the air bubble walls within fishes (such as the swim bladder or air bubbles in the blood) that strike against nearby tissues or from air bubbles within the blood bursting or expanding and damaging tissues (Stephenson et al., 2010). The actual nature of non-auditory physiological effects may range from a very small amount of external bleeding to small internal bleeding to substantial hemorrhage of tissues (such as kidney or liver) to rupture of the swim bladder (see Stephenson et al. [2010] and Halvorsen et al. [2011a,b] for a discussion of the range of potential effects).

There are several potential (and overlapping) consequences of non-auditory physiological effects. One possibility is that the effects heal, and there is no lasting consequence. Alternatively, even if the physiological effect has no direct consequences per se, it is possible that it leads to temporary decreased fitness of the animal until the damage is healed. This could result in the animal being subject to predation, less able to find food, or other consequences that result in death.

Secondly, the effect could result in delayed mortality from events such as continuous bleeding or disruption of tissues (e.g., spleen or liver). Or, the tissue damage itself may not be life threatening, but it may become infected and potentially result in death.

There are few quantified and reliable data on effects of exposure to high intensity sound on body tissues. There are a number of studies showing no tissue damage as a result of exposure of several different species to sonar (Kane et al., 2010), seismic devices (Song et al., 2008), and pile driving (Caltrans, 2010a,b). However, in each of these studies, the swim bladder in the fishes may not have been filled with air, and this could have resulted in less likelihood of damage as compared to situations where the swim bladder is filled to its normal density of air (Halvorsen et al., 2011a,b).

The only quantifiable study documenting a range of physiological effects on fishes comes from exposure of Chinook salmon to 960 or 1,920 strikes of simulated pile driving sounds (Halvorsen et al.,

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[9] Note, there is mortality associated with explosive devices, but this is outside the purview of this appendix. A discussion of the effects of explosives can be found in Hastings and Popper (2005) and Popper and Hastings (2009b).

2011a,b; Casper et al., 2011a). This study demonstrates that effects are graded, with what is likely to be minimal peripheral bleeding at the lowest (but still very intense) sound exposures (210 dB re 1 $\mu Pa^2 \cdot s$ $SEL_{cum}$) to significant bleeding and tissue rupture at the very highest levels presented in the study (219 dB re 1 $\mu Pa^2 \cdot s$ $SEL_{cum}$). Importantly, fish held for a period of time post-exposure showed complete recovery from most of the effects, although the investigators are very careful to point out that recovery took place in a lab tank where fish with slightly lowered fitness would not be subject to predation or disease as may happen in the wild (Casper et al., 2011a).

Indeed, the overall impact on fishes in an ecosystem is low, as only a very small fraction of the fish population will likely be close enough to an intense source to be subject to immediate mortality. The open issues may be (a) injury that can lead to delayed mortality and (b) behavioral effects that lower fitness (e.g., move from migratory routes, leave food sites, and masking of biologically important sounds).

## 5.2. AUDITORY EFFECTS OF EXPOSURE TO INTENSE SOUNDS

Several studies have examined effects of high intensity sounds on the ear. While there was no effect on ear tissue in either the SURTASS LFA study (Popper et al., 2007) or in the study of effects of seismic airguns on hearing (Popper et al., 2005; Song et al., 2008), three earlier studies suggested that there may be some loss of sensory hair cells resulting from exposure to high intensity sources. However, none of these studies concurrently investigated effects on hearing. Enger (1981) showed some loss of sensory cells after exposure to pure tones in the Atlantic cod (*Gadus morhua*). A similar result was shown for the lagena of the oscar (*Astronotus oscellatus*), a cichlid fish, after an hour of continuous exposure (Hastings et al., 1996). In neither study was the hair cell loss more than a relatively small percentage of the total sensory hair cells in the hearing organs. And, in neither case was the sound anything like the high intensity sources of concern today.

Most recently, McCauley et al. (2003) showed loss of a small percentage of sensory hair cells in the saccule (the only end organ studied) of the pink snapper (*Pagrus auratus*), and this loss continued to increase (but never to become a major proportion of sensory cells) for up to at least 53 days post-exposure. This hair cell loss or the ones in the Atlantic cod or oscar would not necessarily have resulted in hearing loss since fishes have tens or even hundreds of thousands of sensory hair cells in each otolithic organ (Popper and Hoxter, 1984; Lombarte and Popper, 1994), and only a small portion were affected by the sound. The question remains as to why McCauley et al. (2003) found damage to sensory hair cells while Popper et al. (2005) did not. The difference in results may very well be associated with differences in species, precise sound source, spectrum of the sound, and sound propagation effects. For example, the Popper et al. (2005) study was in relatively shallow water with poor low-frequency propagation, therefore, the spectrum of sound is likely to have been very different than in the McCauley et al. (2003) study (Hastings, 2009).

One question that arises in the McCauley study is the continued damage to sensory cells after 53 days and whether this would indicate that there was permanent hair cell damage and hearing loss. Since the tissue sampled at each time interval in this study were from different fish, it is impossible to know if the dead cells on Day 53 had been replaced by newly formed cells and what was seen as damage was scar tissue or if the cells that died post-exposure were not replaced. However, based on the considerable data demonstrating hair cell replacement and addition in many fish species, it is likely that even if the cells that were damaged did not get replaced, the high rate of sensory cell proliferation in fishes would have compensated for the small number of lost hair cells (e.g., Corwin, 1981; Popper and Hoxter, 1984; Lombarte and Popper, 1994, 2004).

# 6. EFFECTS OF ANTHROPOGENIC SOUNDS ON BEHAVIOR

Perhaps the biggest issue with regard to effects of anthropogenic sound is the potential effects on fish behavior. Some potential effects can be suggested based on studies of masking and TTS (**Section 4.0**). However, whether TTS or masking actually impacts behavior or whether other behaviors are affected by anthropogenic sound (e.g., leaving a feeding area, changes in migratory paths) is very difficult to study and can only be studied using wild animals in the open water. While investigators have, from time to time, suggested that behavior can be predicted based on responses to sound in tanks, small cages, or larger enclosures, there is always the question as to whether these behaviors are the same as would be encountered in fishes in the wild whose responses were restricted by only their being able to move limited distances. As will be discussed below, there are a few studies that give some suggestion as to the potential responses of wild fishes to sound sources.

However, before discussing those results, it is critical to appreciate the complexities associated with understanding responses of fishes to increased ambient noise and/or the presence of intense sound sources. In fact, fishes may (or may not) show behavioral responses to a sound, and, if a response occurs, the nature of the response may vary widely. It is equally important to note that the nature of a response (or whether there is a response at all) varies depending on the type of signal heard as well as on the motivation of the fishes to respond, the experience of the fishes in the presence of a particular sound or to sounds in general, the age of a fish, and many other factors. Thus, predicting behavior is not simply correlating sound level or type with a behavior and assuming this behavior will show up every time that sound occurs. Instead, a fish may respond to a sound at one time but not at another and the response may be predicated on what the fish is otherwise doing when the sound is presented. Therefore, a fish that is mating may be less likely to respond to an anthropogenic sound than a fish that is simply swimming around, and a fish that has heard the same sound multiple times and does not associate danger with it may not respond, whereas a fish that hears the sound for the first time may respond.

The difficulty of predicting behavior is documented not only in the data on fishes but also from data on hearing for amphibians, birds, and mammals (including humans). These data show, in general, that as sound levels in the environment increase, animals tend to respond in different ways, which often vary depending on the nature of the sound source and sound level as well as on the behavioral state of the animal (e.g., what it is doing) when the sound level changes. Responses of animals vary widely (reviewed in Brumm and Slabbekoorn [2005]). These may include movement from the area of maximum sound level, as shown for several fish species (Engås et al., 1996; Slotte et al., 2004), to changing the intensity of calls so they can be heard over the background sounds (Bee and Swanson, 2007) or changing the spectrum of the emitted sounds so they are no longer masked, as has been shown in a variety of species (Brumm and Slabbekoorn, 2005; Dooling et al., 2009; Parris et al., 2009; Laiolo, 2010; Slabbekoorn et al., 2010).

It is also critical to note that animals (and humans) generally do not respond to sounds when the sounds are just detectable (whether there is background sound or not). Sounds generally have to be well above the minimal detectable level in order to elicit behavioral responses[10]. At the lowest sound levels, the animal may simply ignore the sound since it is deemed "not important" or from too distant of a source. It is only at higher levels where the animal becomes "aware" of the sound and may make a decision that it is important or not to behaviorally respond. To put it into terms of masking, it is possible that the sound has to be sufficiently above the masked threshold of detection for the animal to be able to resolve the signal within the noise and recognize the signal as being of biological relevance.

By way of example, in an experiment on responses of American shad to sounds produced by their predators (dolphins), it was found that if the predator sound is detectable but not very loud the shad will not respond (Plachta and Popper, 2003). But, if the sound level is raised by about 8 or 10 dB, the American shad will turn and move away from the sound source. Finally, if the sound is made even louder, as if a predator were nearby, the American shad go into a frenzied set of motions that probably helps them avoid being caught. It was speculated by the researchers that the lowest sound levels were recognized by the American shad as being from very distant predators and, thus, not worth a response. At somewhat higher levels, the American shad recognized that the predator was closer and started to swim away. Finally, the loudest sound was thought to resemble a very nearby predator, eliciting maximum response to avoid predation.

At the same time, there is evidence from a recent study in Norway (Doksaeter et al., 2009) that fishes will only respond to sounds that are of biological relevance to them. Doksaeter et al. (2009) showed no responses at all from free-swimming herring (*Clupea*) when exposed to sonars produced by naval vessels. Similarly, sounds at the same received level that had been produced by major predators of the herring (killer whales) elicited strong flight responses.

Significantly, the sound levels received by the fishes from the sonar in this experiment were from 197-209 dB (rms) re 1 μPa at 1-2 kHz. In this frequency range, the hearing threshold for herring that are most closely related to those used in the Doksaeter et al. (2009) study is about 125-135 dB re 1 μPa

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[10] Of course, there are exceptions. A parent will respond to the lowest sound produced by their newborn child, and a person walking down a very dark street at night will probably respond to sounds of scraping feet even if they are very quiet.

(Mann et al., 2005). This means that the fish showed no reactions to a sound that is biologically irrelevant even though the sound was up to 84 dB above the fish's hearing threshold (209 dB sonar versus 120 dB threshold).

It is likely that responses from fishes to any noise source, including pile driving, will show gradations in responses similar to the American shad. Therefore, fish responses can be seen as being in several sequential steps (see also **Figure J-2**):

- Fishes do not hear the sound (it is too low and/or masked).
- The sound is at a higher level detectable to the fish, but it is sufficiently low that the sound is "dismissed" as not being biologically relevant or important.
- The sound is somewhat higher above threshold, but the fish cannot discriminate it from the ambient sounds and so still does not respond (e.g., informational masking).
- The sound is clearly audible to the fish and recognizable, but the fish does not respond or makes only an initial, small response (e.g., startle) and then returns to whatever it was doing. In addition, after multiple presentations of the sound, the fish may decide that the sound is not biologically important, and the animal habituates and no longer shows a startle response.
- Sound is even louder, and the fish recognizes it as something that may be biologically relevant and may change behavior (e.g., swim away or change swimming course). But, when the sound ends or after the fish habituates to the sound, the animal returns to what it was doing.
- The fish may totally avoid the very loudest signals if they perceive it as being potentially "harmful" and permanently change location or migratory pattern.

## 6.1. FISH CATCH AND ANTHROPOGENIC SOUND

Several studies have demonstrated that human-generated sounds may affect the behavior of at least a few species of fishes. Engås et al. (1996) examined movement of fishes during and after a seismic airgun study by determining catch rate of haddock (*Melanogrammus aeglefinus*) and Atlantic cod as an indicator of fish behavior. These investigators found a significant decline in catch rate of both species that lasted for several days after termination of airgun use. Catch rate subsequently returned to normal. The conclusion was that the decline in catch rate resulted from the fish moving away from the fishing site as a result of the airgun sounds. However, the investigators did not actually observe behavior, and it is possible that the fish just changed depth. Another alternative explanation is that the airguns actually killed the fish in the area, and the return to normal catch rate occurred because of other fishes entering the fishing areas.

More recent work from the same group (Slotte et al., 2004) showed parallel results for several additional pelagic species, including blue whiting and Norwegian spring spawning herring[11]. However, unlike earlier studies from this group, the authors used fishing sonar to observe behavior of the local fish schools. They reported that fishes in the area of the airguns appeared to go to greater depths after the airgun exposure. Moreover, the abundance of animals approximately 30-50 km (18.6-31.1 mi) away from the ensonification increased, suggesting that migrating fish would not enter the zone of seismic activity.

Similarly, Skalski et al. (1992) showed a 52 percent decrease in rockfish (*Sebastes* sp.) catch when the area of catch was exposed to a single airgun emission at 186-191 dB re 1 μPa (mean peak level) (see also Pearson et al. [1987, 1992]). They also demonstrated that fishes would show a startle response to sounds as low as 160 dB, but this level of sound did not appear to elicit a decline in catch.

Culik et al. (2001) conducted a very limited number of experiments to determine catch rate of herring (*Clupea harengus*) in the presence of pingers producing sounds that overlapped with the frequency range of herring hearing (2.7-160 kHz). They found no change in catch rate in gill nets with or without the higher frequency sounds (>20 kHz) present, although there was an increase in catch rate with the signals from 2.7 to 19 kHz (a different source than that of the higher frequency). The results could mean that the fish did not "pay attention" to the higher frequency sound or that they did not hear it, or that lower

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[11] Scientific names for neither species was given in publication.

frequency sounds may be attractive to fish. There were no behavioral observations to document how the fish actually responded when they detected the sound.

Most recently, Løkkeborg et al. (2011) repeated the earlier study using a somewhat different approach, and the results were different from those found initially. There was some suggestion that the fish in this study did not respond to the seismic sounds in these studies, but comparisons are hard to make because of substantial experimental differences. However, what these results do suggest is that understanding and predicting effects of sound on fishes will not be simple, and that there are many factors that come into play in trying to understand fish behavior.

## 6.2. OTHER BEHAVIORAL STUDIES

There have been a variety of other behavioral studies, none of which provide conclusive evidence that fishes will or will not respond to a particular sound source. For example, Wardle et al. (2001) used a video system to examine the behaviors of fishes and invertebrates on a coral reef in response to emissions from seismic airguns that were carefully calibrated and measured to have a peak level of 210 dB re 1 µPa at 16 m (164 ft) from the source and 195 dB re 1 µPa at 109 m (357.6 ft) from the source. They found no substantial or permanent changes in the behavior of the fishes or invertebrates on the reef throughout the course of the study, and no animals appeared to leave the reef. There was no indication of any observed damage to the animals.

Mueller-Blenkle et al. (2010) examined responses of several penned Atlantic Ocean species to sounds recorded from pile driving, but results were equivocal and could not be used to predict responses of fishes to pile driving. Indeed, responses levels were low, and fishes showed some acclimation to the sounds, suggesting (though not proving) that fishes might learn to ignore high levels of anthropogenic sound over time.

A study by Jorgenson and Gyselman (2009) may provide some insight into how fishes would behave in response to intense anthropogenic sounds[12]. The authors exposed fishes in the Mackenzie River (Northwest Territories, Canada) to seismic airguns and using sonar observed the movements of the fishes. The goal was to determine if a seismic survey, using high intensity sounds for long periods of time, could impact behavior by changing migratory patterns of fishes.

The investigators could not determine the species observed by sonar, but based on known river inhabitants, they suggest that there were a variety of species present, including those used by Popper et al. (2005)[13]. While results may be limited to one or two species, the investigators found that free-swimming fishes observed with sonar showed no response to the airguns with respect to changes in swimming direction or speed, even when sound exposure levels (single discharge) were on the order of 175 dB re 1 $\mu Pa^2 \cdot s$ and peak levels of over 200 dB re 1 µPa.

Finally, Sarà et al. (2007) used divers to observe the behavioral responses of bluefin tuna (*Thunnus thynnus*) in large in-ocean cages (approximately 70 m [229.6 ft] square opening and 30 m [98.4 ft] deep) to noise from passing boats. The results showed that the tuna schools would change depth and some swimming patterns in the presence of sounds from approaching ferries and hydrofoils (normal transport in the region of the cages) and exhibit various other types of behavior in response to sounds from small boats. While these results are potentially of interest in suggesting that at least bluefin tuna may be disturbed by vessel noise, the authors did not provide sound levels received at the fish. Moreover, the fish used are a large oceanic pelagic schooling species (weight of 40-54 kg [88-119 lbs] in this study) and the results may not necessarily apply to other species.

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[12] It should be noted that this study was done on fish in a river, and it is not clear how applicable results would be to fishes in a marine environment and, thus, in a much larger expanse of water in which they can move around.

[13] The Jorgenson and Gyselman study was conducted just after the Popper et al. (2005) investigation and so it is highly likely that the same species, plus additional species, were in the Mackenzie River at the time.

# 7. OTHER ISSUES WITH REGARD TO EFFECTS OF ANTHROPOGENIC SOUNDS

## 7.1. STRESS

Although an increase in background sound may cause stress in humans[14], there have been few studies on fishes (e.g., Smith et al., 2004b; Remage-Healey et al., 2006; Wysocki et al., 2006, 2007). There is some indication of physiological effects on fishes, such as a change in hormone levels and altered behavior, in some (Pickering, 1981; Smith et al., 2004a,b) but not all species tested to date (e.g., Wysocki et al., 2007). Sverdrup et al., 1994 found that Atlantic salmon subjected to up to 10 explosions to simulate seismic airguns released primary stress hormones, adrenaline and cortisol, as a biochemical response. There was no mortality. All experimental subjects returned to their normal physiological levels within 72 hrs of exposure. Since stress affects human health, it seems reasonable that stress from loud sound may impact fish health, but available information is too limited to adequately address the issue.

## 7.2. EGGS AND LARVAE

An additional area of concern is whether high intensity sounds may have an impact on eggs and larvae of fishes. Eggs and larvae do not move very much and so must be considered as a stationary object with regard to a moving sound source. Thus, the time for impact of sound is relatively small since there is no movement relative to the vessel.

There have been a few studies on effects of sound on eggs and larvae (reviewed extensively in Popper and Hastings, 2009b), and there are no definitive conclusions to be reached. At the same time, many of the studies have used non-acoustic mechanical signals such as dropping the eggs and larvae or subjecting them to explosions (e.g., Lagardère, 1982; Jensen and Alderdice, 1983, 1989; Dwyer et al., 1993). Other studies have placed the eggs and/or larvae in very small chambers (e.g., Banner and Hyatt, 1973) where the acoustics are not suitable for comparison with what might happen in a free sound field (and even in the small chambers, results are highly equivocal). A few studies of the effects of high energy sounds on eggs and larvae of invertebrates also provided no definitive evidence of damage, but, like for vertebrates, there are insufficient studies to reach firm conclusions as to the effects of sounds on invertebrates (Lagardère and Régnault, 1980).

Several studies did examine effects of sounds on fish eggs and larvae, and, in all cases, there were no observed effects on normal survival or hatching, including with the use of sounds that mimic those produced by seismic airguns (e.g., Kostyuchenko, 1972). In contrast, Booman et al. (1996) investigated the effects of seismic airguns on eggs, larvae, and fry of different larval stages of cod (*Gadus morhua*), saithe (*Pollachius virens*), herring (*Clupea harengus*), turbot (*Psetta maximus*), and plaice (*Pleuronectes platessa*) in field experiments. They exposed fishes to sound source with peak sound pressure levels, 220-242 dB re 1 $\mu Pa^2$, and found significant mortality, but only when the specimens were within about 5 m (16.4 ft) of the source. The most substantial effects were to fishes that were within 1.4 m (4.6 ft) of the source. While the authors suggested damage to some cells, such as those of the lateral line, few data were reported, and the study is in need of replication. Moreover, it should be noted that the eggs and larvae were very close to the airgun array; at such close distances, the particle velocity of the signal would be exceedingly large. However, the received sound pressure and particle velocity were not measured in this study.

Jørgensen et al. (2005) examined effects of high intensity pure tones from 1.5 to 6.5 kHz on the survival and behavior of larval and juvenile fishes of several species placed in small plastic bags. The study used herring (*Clupea harengus*) (standard lengths 2-5 cm [0.8-1.9 in]), Atlantic cod (*Gadus morhua*) (standard length 2-6 cm [0.8-2.4 in]), saithe (*Pollachius virens*) (4 cm [1.6 in]), and spotted wolffish (*Anarhichas minor*) (4 cm [1.6 in]) at different developmental stages. Both tissue pathology and survival were studied in response to sounds from 150 to 189 dB, and the only effects found were 20-30 percent mortality in one group of herring larvae at the highest sound levels, but this was not replicated.

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[14] The data here are very complex, and there are many variables in understanding how sound may stress humans or any animal. The variables include sound level, duration, frequency spectrum, physiological state of the animal, and innumerable other factors. Thus, extrapolation from human stress effects to other organisms is highly problematic and should be done with only the most extreme caution.

In a follow-up unpublished analysis of these data, Kvadsheim and Sevaldsen (2005) sought to understand whether the mid-frequency continuous wave (CW) signals used by Jørgensen et al. (2005) would have a significant impact on larvae and juveniles exposed to this sonar in the wild. The investigators concluded that the extent of damage/death induced by the sonar would be below the level of loss of larval and juvenile fishes from natural causes, and so no concerns should be raised. The only issue they did suggest that needs to be considered is when the CW signal is at the resonance frequency of the swim bladders of small clupeids. If this is the case, the investigators predict (based on minimal data that are in need of replication) that such sounds might increase the mortality of small clupeids that have swim bladders that would resonate.

Most recently, a group in the Netherlands exposed larvae of common sole (*Solea solea*) to simulated pile driving sounds in an apparatus that is very similar to that used by Halvorsen et al. (2011a,b) for larger fish (de Jong et al., 2011; L.J. Bolle, pers. comm.[15]). The larvae of different stages were exposed to sound with $SEL_{cum}$ of up to 206 dB re 1 $\mu Pa^2 \cdot s$ without any affect on fish mortality. In other words, there were no differences in mortality between fish exposed to the simulated pile driving sound and fish that served as controls. The authors did not, however, look at effects on fish tissue or larval growth, and it is possible that either or both of these would have shown an effect of sound exposure.

## 7.3. INVERTEBRATES

One question that is difficult to answer is the potential effect of high intensity sounds on invertebrates (e.g., crabs and cephalopods). There are almost no data on hearing by aquatic invertebrates, and the few suggestions of hearing indicates that it is for low frequencies and only to the particle motion component of the sound field (e.g., Mooney et al., 2010). There are few data indicating if and how invertebrates may use sound in behavior, although a number of species make sounds and so, presumably, use such sounds for communication (e.g., Budelmann, 1992; Popper et al., 2001). However, there are no data that indicate whether masking occurs in invertebrates or suggest whether sounds from construction would have any impact on invertebrate behavior. The one available study on effects of seismic exploration on shrimp suggests no behavioral effects at sound levels with a source level of about 196 dB re 1 μPa rms at 1 m (3.3 ft) (Andriguetto-Filho et al., 2005).

There are also no substantive data on whether the high sound levels of any anthropogenic sound would have physiological effects on invertebrates. The only potentially relevant data are from a study on the effects of seismic exploration on snow crabs on the east coast of Canada (Boudreau et al., 2009). The preponderance of evidence from this study showed no short-term or long-term effects of seismic exposure in adult or juvenile animals or on eggs.

Two other studies are important to mention, but only because the results are likely to be referenced. It is important to note that both have substantial problems that make them scientifically unsound. An unpublished study by Guerra et al. (2004) suggested that there was damage to body tissues in squid that had possibly been exposed to high intensity naval sonars. However, there is no evidence that the animals were exposed to sonar (only an inference). Moreover, there were no controls for the tissues, and all of the animals had died well before they were accessed by the investigators. During this time, it is highly likely that the tissue went through normal degenerative processes, therefore, it is impossible to know if the damage suggested was from anything other than normal tissue decay. It is also important to note that this work, while in the news, was never published in the scientific literature and that the histological analysis of the tissue has not been made available for examination by other experts.

The second study by André et al. (2011) exposed four cephalopod species (*Loligo vulgaris*, *Sepia officinalis*, *Octopus vulgaris,* and *Illex coindetii*) in a tank to sounds and then, after sacrifice of the animals, examined the statocysts (which are the ears of cephalopods). The authors show that there is some tissue degeneration, and they suggested that the sounds to which the animals were exposed caused the damage. However, there are very substantial problems with this study that open the results, and conclusions, to serious question.

First, the only controls provided were never subject to the same handling as the experimental animals. The only controls should be animals and tissues exposed to precisely the same conditions and procedures

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[15] Personal communication on May 22, 2011 to Dr. Arthur N. Popper. The full report from this study should be released in July 2011 and submitted for publication soon thereafter. Dr. Popper reviewed the report at the request of the Dutch regulatory authority and found it to be an excellent study.

as the experimental other than for the variable in question, in this case the sound. However, this was not done in this study, and so it is very reasonable to suggest that the overall treatment of the experimental animals, including handling, being placed and maintained in the test tank, etc. could have been the cause of any effects noted.

Second, cephalopods, even as indicated by the authors, are detectors of particle motion (just like fishes that do not have specializations to couple an air bubble to the ear). The signals to which the cephalopods were exposed were measured in pressure (something that the animals do not detect), and there was no calibration of the particle motion. Since the exposure was done in a tank with relatively flexible walls, it is impossible to predict the particle motion from pressure measurements. Thus, nothing in this experiment can relate the sound levels and any damage to the statocysts, even if the damage seen was related to the sounds.

Third, to generalize about invertebrates, it is important to note that the lack of any air bubbles (such as the fish swim bladder) that would be set in motion by high intensity sounds leads to the suggestion that there would be little or no impact of high intensity sounds on invertebrates (although, like fishes, if the invertebrates are very close to the source, the shock wave from the source might have a general impact on survival).

Finally, the authors exposed the animals to sound for 2 hrs, which is far longer than any exposure in the wild where the anthropogenic sources of concern, such as sonar and seismic airguns. These are generally moving sources, thus they would expose a slower moving (or stationary) animal for just a few minutes (if not less) rather than 2 hrs.

### 7.4. VESSEL NOISE AND FISH

A growing concern with regard to increases in anthropogenic noise comes from the increasing number of commercial ships that are found over large geographic areas as well inshore and the increasing number of small pleasure craft found inshore and in harbors. All vessels produce sound as a by-product of their operation, which is generally below 1 kHz. Source levels of vessels can range from <150 dB re 1 µPa to over 190 dB for the largest commercial vessels (Richardson et al., 1995; Hildebrand, 2009).

Vessel noise produces sounds in the general hearing range of fishes (Amoser et al., 2004). Continuous exposure (30 minutes) to boat noise has been shown to increase fish cortisol levels (stress response) (Wysocki et al., 2006). Temporary threshold shift has been associated with long-term, continuous exposure (2 hrs), and masked hearing thresholds have also been recorded for fishes exposed to noise from small boats and ferries (Scholik and Yan, 2001; Vasconcelos et al., 2007). Additionally, vessels (i.e., trawlers, ferries, small boats) can change fish behavior (e.g., induce avoidance, alter swimming speed and direction, and alter schooling behavior) (Sarà et al., 2007). Studies do not indicate precisely which of these kinds of physical or behavioral effects may result from a single ship or from an aggregation of shipping activity, although it is important to bear in mind that the large number of commercial vessels, their nearly continuous presence in many nearshore areas, and projected increases in shipping trends. One of the most serious implications of this increase in shipping noise is the impact it may have in terms of masking sounds of biological origin and affecting communication between fishes.

The sounds produced by motor-driven ships causes herring to dive and swim away from the vessel (Mitson and Knudsen, 2003). Paradoxically, research vessels specially designed to reduce noise can result in an even greater behavioral reaction (Ona et al., 2007). Sand et al. (2008) have pointed out that passing ships produce high levels of infrasonic and low-frequency noise (>10-1,000 Hz), and that infrasonic frequencies may be responsible for the observed avoidance reactions.

## 8. GENERAL CONCLUSIONS – EFFECTS

The data obtained to date on effects of sound on fishes are very limited both in terms of the number of well-controlled studies and in the number of species tested. Moreover, there are significant limits in the range of data available for any particular type of sound source. While new data have become available on physiological effects of very intense pile driving (Casper et al., 2011a; Halvorsen et al., 2011a,b) and these data may be carefully extrapolated to other sound sources and species, the data are still very limited and comparable data are needed for other sources and species.

At the same time, physiological effects are probably not the major issue with regard to anthropogenic sound since most fishes will not be close enough to a sound source to show such effects. Instead, the biggest issues are related to effects on behavior since anthropogenic sources could, potentially, impact behavior of fishes over broad areas. Yet, despite this clear need for understanding of behavioral effects, the extent of data is exceedingly limited and equivocal; it is not yet possible to make clear statements about effects of any particular sound source on the behavior of any species.

The following sections briefly review and comment on the effects discussed earlier in this report. At the same time, it should be noted that after examining the complete literature on effects of sound on fishes (and turtles), an international panel of experts reached the conclusion that there are insufficient data to reach conclusions for most any sound source[16].

The BOEM concludes that there is incomplete or unavailable information (40 CFR 1502.22) about the effects of sound on fish, in particular how loud sound may stress fish and influence their health. At issue also is our ability to understand what fish experience when we observe or interpret fish response to stimuli, such as airguns. While there will never be complete scientific information on the fish species that live in OCS waters of the AOI, a body of biological and physiological data and information about the effects of sound on fish is available to us. We report where limited data and insufficient knowledge challenge our ability to understand these effects. The acquisition of a much more complete knowledge base for fish using the AOI cannot be acquired without exhorbitant cost. It certainly cannot be acquired in a time frame to make it available for this evaluation.

The BOEM has therefore determined that data or information on the effects of sound on fish identified as incomplete or unavailable is not essential to a reasoned choice among the alternatives, including the No Action alternative. We are able to draw basic conclusions despite incomplete or unavailable information, discuss results using available scientifically credible information, and apply that information using accepted scientific methodologies.

## 8.1. PHYSIOLOGICAL EFFECTS

Several general points can be made with reference to effects on fish physiology and mortality of intense sounds.

1. There is little evidence for immediate mortality other than when fishes are very close to intense sound sources, such as pile driving for very large piles. There are no data on any other sound source. Substantial study needs to be put into questions of immediate mortality.
2. Physiological effects that are sufficient to potentially kill fishes over time appears to have some correlation with the total amount of sound exposure. A few non-quantified studies have shown no damage to non-auditory tissues as a result of seismic airgun exposure (Popper et al., 2005; Song et al., 2008) or to any tissue after exposure to high intensity low-frequency and mid-frequency sonars (Halvorsen et al., 2006; Popper et al., 2007). A quantified study of pile driving (Halvorsen et al., 2011a,b) demonstrates a range of effects that increase in likely impact on the animals, but the fishes seem to recover from these effects in a few days (Casper et al., 2011a). There are some data that suggest that some seismic airgun signals, under certain acoustic conditions, may damage sensory cells of the ears (McCauley et al., 2003), but that there is no effect on other species under different acoustic conditions (Song et al., 2008).
3. There are very few data documenting effects of any intense sound source on eggs and larvae. Far more data are needed before any preliminary conclusions can be reached on the effects of sound on eggs and larvae, and studies need to include, in addition to mortality, effects on growth and body tissues.
4. It is possible that exposure to loud sounds or increased background noise can result in increased stress levels and effects on the immune system. However, such effects have never been documented for fishes, and the only long-term study (Wysocki et al., 2007) of

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[16] This panel was co-chaired by Drs. Arthur Popper and Richard Fay, and a report is in preparation. The work was done under the auspices of the Standards Group of the Acoustical Society of America and was funded by several U.S. and international agencies and organizations. The report cannot be provided at this point, but will be provided as soon as possible.

increased ambient noise showed no effect. It is critical to note that lack of effect may be more a function of not enough study rather than being the actual result. Future studies are needed to ask questions of such effects.

## 8.2. EFFECTS ON FISH BEHAVIOR

The more critical issue for effects of anthropogenic sound on fishes, however, is the effect on the behavior of wild animals and whether sound exposure will alter the behavior of a fish in a manner that will affect its way of living – such as where it tries to find food or how well it can find a mate. With the exception of just a few field studies, there are no data on behavioral effects, and most of these studies are very limited in scope and all are related to seismic airguns. Because of the limited ways in which behavior of fishes in these studies were "observed" (often by doing catch rates, which tell nothing about how fishes really react to a sound), there really are no data on the most critical questions regarding behavior.

Indeed, the fundamental questions are how fishes behave during and after exposure to a sound as compared to their "normal" pre-exposure behavior. This requires observations of a great number of animals over a large area for a considerable period of time before and after exposure to sound sources as well as during exposure. Only with such data is it possible to tell how sounds affect overall behavior (including movement) of animals. These experiments are very difficult to do, require a large amount of resources, and are very expensive to conduct.

## 8.3. INCREASED BACKGROUND SOUND

In addition to questions about how fish movements change in response to sounds, there are also questions as to whether any increase in background sound has an effect on more subtle aspects of behavior, such as the ability of a fish to hear a potential mate or predator or to glean information about its general environment. There is a body of literature that shows that the sound detection ability of fishes can be "masked" by the presence of other sounds within the hearing range of the fishes (reviewed in Fay and Megela-Simmons, 1999; Popper et al., 2003). Just as a human has trouble hearing another person as the room they are in gets noisier, it is likely that the same effect occurs for fishes (as well as all other animals). In effect, acoustic communication and orientation of fishes may potentially be restricted by noise regimes in their environment that are within the hearing range of the fishes. Perhaps this is the single most important area for future study since the masking effects of anthropogenic sounds could have a direct impact on the ability of fishes to hear sounds relevant to survival.

# 9. CURRENT CRITERIA

There is considerable national and international concern about effects of anthropogenic sound on marine organisms, including fishes (see Popper and Hawkins [2011]). However, despite the concerns, there is actually very little in the way of recommendations for regulatory levels of sound. In fact, the only known criteria, which are clearly labeled "interim," arose on the U.S. West Coast out of concern about effects of pile driving on fishes (reviewed in Woodbury and Stadler, 2008; Stadler and Woodbury, 2009). These criteria are for the onset of physiological effects and say nothing about behavior.

The current interim criteria are dual in nature. That is, they state that physiological onset may occur if the peak sound level of a pile driving strike is 206 dB re 1 µPa or have an $\mathrm{SEL_{cum}}$ of 187 dB re $1\mu\mathrm{Pa}^2$-s for fishes above 2 g (0.07 oz) or 183 dB re $1\mu\mathrm{Pa}^2$-s for fishes below 2 g (0.07 oz) (for explanation of these criteria, see also Popper et al. [2006] and Carlson et al. [2007]).

The levels for the current interim criteria were substantially criticized as not being based on the best available science at the time of their implementation (see Carlson et al. [2007] for detailed recommendations that were not used in setting the current interim criteria). Presently, based on a wide range of data that arose concurrent or subsequent to the current interim criteria, it is clear that the set levels, at least for cumulative exposure, are far too low and unrealistic for onset of physiological effects.

The inadequacy of the interim criteria has now been documented in a recent quantified study on the effects of pile driving on the onset of physiological effects in Chinook salmon (Halvorsen et al., 2011a,b) and several other species (Casper et al., 2011a). These studies, which demonstrated that an $\mathrm{SEL_{cum}}$ below approximately 207 dB re $1\mu\mathrm{Pa}^2\cdot$s will not result in the onset of injury and that $\mathrm{SEL_{cum}}$ as high as

210 dB re 1µPa$^2$·s produces physiological effects that are inconsequential (e.g., minor external bleeding). While these data need to be replicated for other species and other sounds, they have been shown to be appropriate for three very different species, suggesting that there may be reasonably broad applicability of these values for setting future interim criteria.

At the same time, these results are only for pile driving. It is not clear which aspect(s) of intense sounds result in physiological onset, but it is likely that the rise time (onset time) of the signal may be of consequence. Thus, signals with slower rise times than pile driving may have even higher onset levels whereas sounds with faster rise times (e.g., from explosives) may have somewhat lower criteria.

One other factor that must be recognized with these criteria is recovery time, which is built into the West Coast interim criteria (Stadler and Woodbury, 2009). That is, all tissues, when damaged, start to recover as soon as the stimulus is removed. This has been documented in mammals exposed to intense sounds (reviewed in Popper and Hastings, 2009b), and it is more than likely that the same thing happens for fishes. Indeed, Popper et al. (2005) showed recovery of hearing loss resulting from exposure to seismic airguns within 18 hrs of the termination of exposure. Thus, if a fish is exposed to pile driving, the accumulation of exposure (the $SEL_{cum}$) is returned to zero (0) after 12 hrs without exposure (Carlson et al., 2007; Stadler and Woodbury, 2009).

This same restart of accumulation is important for any sound exposure condition. Thus, no matter whether a fish is exposed to pile driving, seismic airguns, sonars, etc., accumulated energy returns to zero after some period of non-exposure.

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