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REVIEW

The effects of human-generated sound on fish

Arthur N. POPPER[1] and Mardi C. HASTINGS[2]

[1]Department of Biology, University of Maryland, College Park, USA and [2]Applied Research Laboratory, The Pennsylvania State University, State College, USA

Abstract

There is growing international concern about the effects of human-generated sound on fish and other aquatic organisms. However, because of a striking paucity of well-designed and controlled experimental data, very little is actually known about the effects of these sounds on fish. Findings suggest that human-generated sounds, even from very high intensity sources, might have no effect in some cases or might result in effects that range from small and temporary shifts in behavior all the way to immediate death. At this point, however, it is nearly impossible to extrapolate from results with one sound source, one fish species, or even fish of one size to other sources, species, or fish sizes. The present paper briefly discusses the potential effects of sound on fish, describes some of the more recent well-controlled experimental studies, and points out areas for future study that will be needed before a real understanding of the effects of sound on fish can be developed.

Key words: anthropogenic sound, behavior, hearing, noise, sound.

INTRODUCTION

Jacques Cousteau's 1956 movie *The Silent World* opened up the seas to international audiences. However, despite sharing the fascination and beauty of the undersea world, Cousteau "perpetrated" the idea that the oceans were silent places where sound had no role in life.

Of course, we now know that the correct name for the movie should have been *The Noisy World* and that sound plays a central role in the lives of many marine organisms.

Correspondence: Arthur N. Popper, Department of Biology, Center for Comparative and Evolutionary Biology of Hearing, University of Maryland, College Park, MD 20742, USA. Email: apopper@umd.edu

Of course, when thinking about sound and marine organisms, one's first thought naturally turns to "communication" between organisms. Indeed, many marine organisms use sound to communicate as a prelude to or during mating, in aggregating, in warning of danger, and probably in many contexts that we have yet to understand.

However, we are also beginning to realize that communication between individuals or groups of animals is certainly not the only role for sounds. As Bregman (1990) points out, the world abounds with sound and animals use sound to glean a great deal of information about their environment. This concept, often referred to as the "auditory scene," provides animals with a 3-D view of their world that often extends far beyond the other senses.

Therefore, an animal that has a sense of sight can develop a "visual scene" of its world. However, this scene is limited to relatively short distances (depending on environmental clarity and brightness) and is within the visual field of the receptors. The auditory scene, however, might extend much further than the visual scene and provides animals with a very broad "view" of their world.

The source of information in the auditory scene is potentially very extensive. Instead of being limited to sounds of conspecifics, the auditory scene might include sounds made by other species (the idea of "interception" that was introduced by Myrberg [1980]) as well as environmental sounds such as raindrops on the water surface, the sounds of a reef, and geologic sources. All of these sounds potentially serve to "inform" an organism about its world. Indeed, the idea of the auditory scene is not limited to the marine environment but is just as relevant to animals on land or in the air. (It has been suggested that some birds migrate using infrasound produced by winds moving over geologic features [e.g. Hagstrum 2001].) And humans constantly make use of the auditory scene in their daily lives, even if they are only aware of many of these sounds when the sounds change or there is a sudden new sound in the environment (e.g. the siren of a fire engine or the cry of a baby).

One significant consideration regarding the auditory scene is that it might have actually been a strong selective factor in the evolution of hearing (Fay & Popper 2000). Clearly, acoustic communication would not have been an initial selective force in the evolution of hearing because it could not occur unless an animal could first detect sounds. Therefore, hearing had to have evolved before acoustic communication. One can imagine that the marine environment was already noisy even before animals made intentional sounds. Van Bergeijk (1967) proposes that the first sound-detecting organs were actually accelerometers that had evolved for the detection of the animal's position relative to gravity. Because such detection might have helped animals detect predators and prey, there might have been strong selective pressures for improving receptor bandwidth and sensitivity. Finally, once animals were able to detect sound and the auditory scene, it is not hard to see the strong selective advantage to developing more sophisticated features of hearing, such as sound source location and sound discrimination, and that these capabilities could readily lend themselves to being used in acoustic communication and its evolution.

The "bottom line" is that detection of the auditory scene has, and continues to be, a critical role in sound detection along with detection of communication signals. As such, anything in the environment that alters the ability of an organism to detect and/or analyze its auditory scene can potentially have a detrimental impact on the life of an animal as well as its species survival.

"INTERFERENCE" WITH THE AUDITORY SCENE

Many studies on hearing in fish and other animals have revolved around measuring the lowest sound level that an animal can detect at a particular frequency. This lowest level is often referred to as the "threshold" of detection or the "absolute threshold." Such thresholds are generally measured in a very quiet environment, such as a soundproof room. This absolute threshold does not, however, generally represent hearing in the real world. In the real world, there is often a wide range of sound that might interfere with or mask the detection of a signal of interest to an animal. As a consequence, thresholds measured in the presence of masking sounds will often be considerably higher than thresholds measured in the quiet. In effect, background sounds make hearing capabilities less sensitive to low-level signals. Therefore, to be detected, a signal of interest has to be more intense in locations where there are masking sounds than where there are no masking sounds. It is generally the case that a masker is more effective, or makes hearing more difficult, when the frequencies in the masker are close to those of the biologically relevant signal.

THE "NATURAL" AQUATIC WORLD

The aquatic world is not quiet. There are numerous sources of sound that present a background of noise that humans encounter in the terrestrial environment. Sounds of the aquatic environment come from abiotic and biotic sources. Abiotic sources might include movement of water across a coral reef, geologic events, waves hitting a shore, and raindrops on the water surface. Biotic sources include fish, whales and invertebrates (snapping shrimp possibly being the most ubiquitous source of background biotic noise in many parts of the world). Many of these organisms produce sounds to communicate over short and long distances with mates, offspring and other conspecifics, or to find prey and identify other objects of interest using echolocation.

Without any question, sound is critically important to aquatic animals for all aspects of their lives. Anything that interferes with the detection of sound has the potential to have a significant impact on the lives of these organisms and affects not only individual animals but also reproduction and the survival of species.

THE AQUATIC WORLD IN THE 21ST CENTURY

For the past 20 or more years, it has been recognized that the aquatic acoustic environment is not limited to biotic and natural abiotic sources. Instead, there is a growing realization that abiotic sources increasingly include a wide range of human-generated sounds. In addition, there is growing concern that these sounds are not only affecting animal hearing and the ability to communicate (e.g. increasing masking levels in the environment), but that they might also have more immediate and substantial effects that could include anything from animals moving from feeding sites to their immediate death (see NRC 1994, 2000, 2003; Richardson *et al.* 1995; Popper 2003; Popper *et al.* 2004; Wartzog *et al.* 2004; Hastings & Popper 2005). The trouble, as discussed below, is that although there is much worry and speculation about the potential effects of human-generated (anthropogenic) sounds, there are only a few studies that really provide useful and usable data to help us understand the effects of these sounds.

The sources of anthropogenic sounds are extensive. They include, to name a few, boats and ships, seismic exploration devices, construction activities, and active sonars. Boats are a major source of noise. Noise from boats is not limited to just supertankers and larger vessels (both of which put out relatively high noise levels). Noise is also produced by pleasure and fishing boats in harbors that might raise background sound levels considerably, especially on a warm summer day. Seismic devices, generally air guns, are used around the world for oil exploration and for studies on undersea geology. Construction activities, such as pile driving, are generally found near shore. Pile driving is used for the building of bridges, wind farms, ports, and numerous other things. Sonars, which might be the most significant open ocean anthropogenic sound source other than ships, are used not only by navies but also by the shipping and the fishing industries and the oceanographic research community.

The question then is: how much do these and other sound sources raise the ambient noise environment? The answer, at least to this point, is severalfold. First, we do not really know the answer because we do not have background noise levels from preindustrialized times (i.e. the early 1800s) when there were really no sounds put into the ocean (NRC 1994, 2000, 2003). As soon as steam shipping arrived, noise levels no doubt started to rise.

Second, it is very clear that the ocean noise level varies in different parts of the world. Whereas the noise levels might be very low in waters around South Australia, harbor noise in the same country might be very high due to shipping. Similarly, noise levels close to coastal USA might be far higher than in midocean and the levels of sound near a harbor with heavy shipping might be far higher than in other locales. Therefore, using a single set of numbers for ocean ambient noise, such as the traditional Wenz curves (1962), is now known not to be realistic (e.g. NRC 2000; Andrew *et al.* 2002).

POTENTIAL EFFECTS OF ANTHROPOGENIC SOUND ON FISH

Although a major concern is that anthropogenic sounds affect communication and detection of the acoustic scene, there is a broad range of other potential effects of these sounds, especially when they are very loud or when they are less intense but long lasting. The contrast between the two sound types is often that the exposure to intense sound sources is relatively brief because the sounds are in a localized area and the sources are often moving (e.g. sonars and seismics) and go by the fish or they are stationary (e.g. pile driving) and the fish swim by. In contrast, the long-lasting sounds, such as might be found in a harbor with heavy shipping or in an aquaculture facility, are pervasive throughout a large region and cannot easily be avoided.

The range of potential effects from intense sound sources, such as pile driving and seismic air guns, includes immediate death. Alternatively, effects could include tissue damage that might or might not directly result in death but that might make the fish less fit until healing takes place, resulting in lower chances of survival. There is also the potential for temporary hearing loss due to exposure to intense sound sources, and this too could lower fitness until hearing recovers. Behavioral changes might also occur, resulting in animals leaving feeding or reproduction grounds. Of course, there is also the possibility that there is no effect of exposure to intense sources, especially if the received level of the sound is not great.

It is possible that less intense but longer lasting sounds, such as those produced by continuous boating, cause a general increase in background noise in some locations. Although it is not likely that such sounds will kill per se, there are concerns that such sounds will result in masking of biologically important sounds, cause some hearing loss, and/or have an impact on stress levels and on the immune system.

THE ISSUE OF METRICS

A significant issue in understanding the effects of sound on fish is how the exposure of one sound source to another can be compared because the acoustic characteristics of different sources vary considerably. The problem is further confounded because the effects result from the sound *received* by the animal, which depends not only on the characteristics of the source but also on the characteristics of the surrounding environment and how they affect the sound field. It is clear, however, that just describing a sound in terms of its peak or root-mean-square (rms) pressure does not provide a full picture of the exposure, especially when the sound is relatively long lasting and has a complex temporal structure.

To try and better characterize sound sources, Hastings and Popper (2005), after critically reviewing all available data, recommend noise-exposure criteria for fish. However, the primary metric they use, sound exposure level (SEL), is based on criteria developed for marine and terrestrial mammals, including humans. "Sound exposure" is simply the integration over time of the square of the sound pressure. And, SEL is sound exposure expressed on a decibel scale referenced to one square micropascal and 1 s. No systematic studies have been conducted for any fish species to determine if SEL is the metric that correlates with hearing loss or damage to auditory and nonauditory tissues, but we do know that in some fishes, effects have been observed when lower levels of sound are applied over longer periods of time than higher levels. Therefore, in the absence of data, SEL seems a reasonable choice for a metric for noise-exposure criteria.

The issue of metrics for hearing loss in fish is confusing because their inner ear responds directly to acoustic particle motion rather than pressure. However, nearly all fish hearing studies report thresholds and threshold shifts using sound pressure so few, if any, data are available with respect to particle motion. In addition, no data are available for the "onset" of auditory temporary threshold shift in fish, even based on sound pressure, because most of the exposure studies have been designed to determine the effect of a particular source operating at sound pressure levels typical of its use in the field. Therefore, fish temporary threshold shift data found in the literature are asymptotic, meaning that additional sound exposure will not result in additional threshold shift. Because we do not know at what point during an exposure the threshold shift becomes permanent and cannot be reversed, it would be best to develop criteria based on the "onset" of temporary threshold shift if such data were available.

The best data available for nonauditory tissue damage are from blast studies (Yelverton *et al.* 1975; Govoni *et al.* 2003). These data show that tissue damage and mortality correlate with an energy metric that accounts for both variations in pressure level and the time duration of the exposure. Because juveniles and fry have less inertial resistance to the motion of a passing sound wave, they are potentially more at risk for nonauditory tissue damage than adult fish. So metrics for tissue damage should be scaled with the mass of the fish.

DATA EXAMINING THE ANTHROPOGENIC EFFECTS OF SOUND ON FISH

A number of papers and reports have examined the effects of sound on fish. However, as discussed extensively by Hastings and Popper (2005), the vast majority of these data are in the form of reports and other documents that have not undergone scientific peer review. Although some of these studies are excellent, many have significant methodological or interpretation problems. Therefore, although such studies are often widely cited as documenting the effects of sound on fish, they do not have results that stand up when subject to critical analysis.

There is a smaller body of data in the peer-reviewed scientific literature that gives some guidance as to the effects of sound on fish. However, it must be realized at the onset that these papers are very few in number, that only a few species have been studied, and that most papers use different types of sounds.

The lack of data makes it very hard to compare results between studies and to extrapolate data from one sound type or species to another. More specifically, although there are some data on the effects of low-frequency sonar (e.g. 100–400 Hz) on rainbow trout (*Oncorhyncus mykiss*, Walbaum, 1792) (Popper *et al.* 2007), it is not clear that these findings for low-frequency pure tones and frequency sweeps tell us much about the effects of midfrequency sonar with energy at higher frequencies (1–10 kHz), much less about possible effects of transient sounds, such as pile driving. Similarly, rainbow trout, although perhaps being suitable to understanding the sound effects on related salmonids, might give us no information about the effects of the same sounds on fishes with better hearing capabilities.

High-intensity sources: pile driving

The high-intensity sources of most interest are pile driving, sonars, and seismic air guns. Each of these is discussed briefly, and additional references are given.

Although it has been argued that fish are killed if they are sufficiently close to pile driving, there are insufficient controlled data to indicate the percentage of fish killed, whether there are any species that are more susceptible to the sounds than others, and the distance at which fish are killed (reviewed in Hastings & Popper 2005). It is possible that fish outside the kill zone are damaged and that this damage would lead to death, but there are no data to support or refute such a suggestion. Moreover, there are numerous complexities with pile driving that might impact the effects on fish. For example, different types of piles (steel or concrete) have different response characteristics and sound spectra. It is not known whether such characteristics will cause a difference in effects. Nor is it known whether there is a cumulative effect from being exposed to multiple pile strikes (which often come as frequently as one per second) and whether any cumulative effect would be altered by changing the time between strikes. The question, in effect, is whether each pile-driving strike is a totally separate event in terms of potential damage to fish or whether multiple events add up to accumulate potential damage. The effect might result in death, tissue damage, and/or hearing loss. At this time, however, virtually nothing is known about such effects from pile driving.

High-intensity sources: seismic air guns

Seismic air guns are used around the world to do underwater geological surveys. These arrays of high-intensity devices project sound down toward the water bottom and into the substrate. The air guns are towed by a moving boat. Long strings of hydrophones pulled behind the air gun array detect the reflected signals. These data provide information about the geological substrate and potential deposits of oil and gas. The peak source level of a seismic air gun array can exceed 250 dB re 1 μPa, and although the bulk of the energy is projected downward, there is considerable lateral energy as well.

There have been substantially more peer-reviewed studies on seismic devices than on pile driving. McCauley *et al.* (2003) demonstrate that shots from a single seismic air gun can cause some damage to the sensory hair cells of the saccule of the ear of the pink snapper (*Pagrus auratus*, Forster 1801). Damage occurred in small regions of this hearing end organ, and it increased for at least 54 days postexposure. McCauley *et al.* did not measure whether hearing loss was associated with the loss of sensory cells. However, they did note that there was no fish mortality and that the fish continued to feed for the whole postexposure time.

Popper *et al.* (2005) exposed several different species of fish to shots from a small seismic air gun array in a river and found no damage to sensory hair cells of the ear (Song *et al.* 2008). However, two of the three species tested showed some hearing loss compared to control animals, although there was complete recovery of hearing within 18–24 h after exposure. There are questions as to why there was hair cell damage in the McCauley *et al.* (2003) study but not in the Popper *et al.* (2005) study. There were several differences between the two studies, however, including spectral characteristics of the signal (possibly a result of different seismic devices and/or water depth), species, and duration of exposure. Although we cannot explain the differences in the results, they do highlight the difficulty in extrapolation between experiments with the limited amount of data we currently have.

Skalski *et al.* (1992) showed a 52% decrease in rockfish (*Sebastes* sp.) catch when the area of catch was exposed to a single air gun emission resulting in a received level of sound at 186–191 dB re 1 μPa (mean peak level) (see also Pearson *et al.* 1987, 1992) These investigators also found that fishes would show a startle response to received sounds as low as 160 dB, but this level sound did not appear to elicit a decline in catch. The basis for the decrease in catch is not clear, and it should be noted that, for the most part, there was no actual visual observation of the behavior of the fish during air gun exposure.

Engås *et al.* (1996) and Engås and Løkkeborg (2002) look at the effects of a seismic exploration on fishing success for haddock (*Melanogrammus aeglefinus,* L., 1758) and Atlantic cod (*Gadus morhua*, L., 1758). They found that, compared to preseismc catches, there was a significant decline in the long-line catch rate during and after the seismic study. The catch rate did not return to normal for at least five days after the end of the seismic study. More recently, the same group used sonar to observe the behavior of blue whiting and Norwegian spring spawning herring during a seismic operation and observed that fish would dive away from the seismic source and not return until after the activity had stopped (Slotte *et al.* 2004).

Although these behavioral studies suggest that there might be some changes in fish behavior associated with seismic air gun activity, a study by Wardle *et al.* (2001) that actually observed fish behavior on a reef off Scotland as an air gun was fired at a level that was measured to be 210 dB re 1 μPa at 16 m from the source and 195 dB re 1 μPa at 109 m from the source found results to the contrary. The investigators found that several species of fish showed virtually no response to the air gun emission other than perhaps a transient startle response that did not change in any way the pattern of movement of the fish.

High-intensity sources: sonar

Since World War II, the navies of the world have been using active sonar to detect and localize submarines. The sonar used varies in frequency depending on the specific mission, but recently, the US Navy deployed SURTASS LFA (low frequency active) sonar that operates below 500 Hz in an effort to locate and find small and quiet diesel-electric submarines. Therefore, there has been growing concern, particularly in the marine mammal community, that high-power sonars could be interfering with acoustic communication or even physically harming animals.

The concern with regard to sonar now extends to fish, and a few studies have tried to address these issues. Popper *et al.* (2007) and Halversen *et al.* (2006) exposed several different species of fish, including rainbow trout (*Oncorhyncus mykiss*) and channel catfish (*Ictalurus punctatus* Rafinesque, 1818), to emissions from the SURTASS LFA sonar. This study was conducted using an actual sonar transducer and exposing fish to received sounds as high as 193 dB re 1 μPa (rms) continuously for up to 216 s. The results indicated no mortality and no damage to auditory and nonauditory tissues but some temporary threshold shift (hearing loss) in both species. Hearing loss recovered within 48 h in channel catfish, and there were not enough data to determine recovery in rainbow trout, but they had not yet recovered after 48 h.

In a nonpublished but very well conducted study in Norway, Jørgensen *et al.* (2005) examined the effects of 100 pulses of 1-s duration of pure tones at 1.5, 4 and 6.5 kHz with received sound levels varying in different experiments from 150 to 189 dB on the behavior of larval fish of several species. The fish were in small chambers and so the acoustic field was not necessarily as precise as that found in the aforementioned LFA study. However, results showed no significant effect on behavior or fish tissue. Although the investigators reported some mortality in larval fish exposed to the highest sound levels used, there were no replicates at this stimulus level. Moreover, in a companion paper, Kvadsheim and Sevaldsen (2005) demonstrate that even if there was this mortality, the likelihood of mortality from larvae dying from exposure to this sound in the wild is substantially less than normal mortality for the same species.

As with other sound sources, the limited data on the effects of sonar show no evidence of fish mortality or tissue damage. Although low-frequency sonars might produce temporary hearing loss in some species, Halvorsen *et al.* (2006) and Popper *et al.* (unpublished data, 2007) found no hearing loss (and no mortality or tissue damage) in several other species.

Increased background noise

Unlike most of the higher intensity sources, lower intensity sounds, such as those produced by increases in shipping and pumps in aquaculture facilities, are continuous and pervade a whole environment. Therefore, although an intense source often passes a fish quickly or the fish can pass it quickly, it is far harder for a fish to get away from general increases in background noise. Indeed, it is well known that humans exposed to long-term increases in background noise, such as might be encountered in a workplace, can wind up with temporary or permanent hearing loss and/or other physiological effects associated with stress.

There have been several studies that have examined the effects of long-term noise exposure on fish (e.g. Smith *et al.* 2004a,b, 2006; Scholick & Yan 2001, 2002; Amoser & Ladich 2003; Amoser *et al.* 2004; Wysocki *et al.* 2006). In general, these studies show that fishes that have anatomical specializations that make them better able to detect lower levels of sound pressure (i.e. hearing specialists) than other fishes might show temporary hearing loss when exposed to increased background noise levels for 24 h or more, whereas fishes without such specializations (i.e. hearing generalists) do not necessarily show hearing loss. For example, Smith *et al.* (2004a,b) examined hearing loss after over 20 days of exposure to a broadband noise of 170 dB re 1 μPa (rms) and found that there was a substantial hearing loss in goldfish (*Carassius auratus* L., 1758), a fish with hearing specializations making it more sensitive to sound pressure, but not in the Nile tilapia (*Oreochromis niloticus* L., 1758), a fish without such specializations. Similar findings for hearing specialists and generalists have been reported by others

(Scholick & Yan 2001, 2002).

These results lead to the tentative suggestion that the amount of hearing loss that occurs in fish might be correlated with the sound pressure level of the noise relative to the hearing threshold of the fish. In other words, as first pointed out by Hastings *et al.* (1996), it is likely that a sound pressure has to be at least some level above a fish's threshold before any hearing loss occurs. Therefore, goldfish, with lower hearing thresholds (better pressure sensitivity), showed hearing loss because the sound pressure level was much further above threshold than for the Nile tilapia.

Further complications in understanding effects of sound on fish

Hastings *et al.* (1996) and McCauley *et al.* (2003) clearly make the point that it will be very hard to extrapolate data on the effects of sound on fish between species until we have considerably more data on different species. Although this point is still critical to any analysis of the effects of sound on fish, we are beginning to appreciate that there are added complications that might make it even harder to extrapolate data between species or between sound sources. The additional complications (that we now know of, and there might be others) include the developmental history of fish and/or genetics. Two observations highlight these points.

In the study of SURTASS LFA sonar, Popper *et al.* (2007) used two different stocks of rainbow trout in 2 successive years. The experimental paradigm was identical in both years. Popper *et al.* (2007) found that the first-year batch of rainbow trout showed a hearing loss to the LFA sound, whereas the fish from the second year showed no hearing loss to the same sounds. The question arose as to the reason for the difference in results. Although there is no clear answer to this question, the fish in both years came from the same fish farm and were raised in the same way. However, because the fish were from eggs of different years, it is likely that the parentage or the genetics of the two groups was different. Or it is possible that there were some developmental differences in the stocks, such as the time between when the eggs were fertilized and allowed to develop. (Typically in aquaculture, eggs are fertilized and then chilled to prevent immediate development. Only when the fertilized eggs are received at the hatchery are they warmed and development starts.) These findings lead to the suggestion that factors in addition to species might have to be taken into consideration when investigating the effects of sound on fish.

These findings are supported by a study in which two groups of rainbow trout were exposed to increased background sounds in an aquaculture facility to determine if long-term (9-month) exposure would result in hearing loss or changes in growth and/or general health (Wysocki *et al.* 2007). Both groups of fish were from the same genetic stock, but one group was kept from development for several weeks longer than the other. The investigators found no effect on hearing or animal health after 9 months of continuous sound exposure in either test group. However, they found that over the whole 9 months, the fish from the group that was kept longer before development started had significantly poorer hearing sensitivity than the fish that started to develop sooner post-fertilization.

BEHAVIOR AND SOUND EXPOSURE

Although most of the studies have been directed at asking whether sounds affect fish physiology, perhaps the far more important question is whether human-generated sounds have any impact on normal behavior. The response to sounds by fish might range from no overt change in behavior to the fish exhibiting a mild "awareness" of the sound or a startle response but otherwise no change in behavior (e.g. Wardle *et al.* 2001) to small temporary movements for the duration of the sound to larger movements that might displace fish from their normal locations (e.g. Slotte *et al.* 2004) for short or long periods of time. There is also the possibility that the sounds will change the migration routes of fish. Depending on the level of behavioral change, there might be no real impact on individuals or populations of fish or there might be substantial changes (e.g. movement from a feeding or breeding site) to affect the survival of a population.

The problem arises that observations of the effects on behavior cannot be undertaken in the laboratory. For example, although Popper *et al.* (2007) observed the behavior of their test animals in a large experimental test tank during exposure to intense low-frequency sonar signals, the observations only show how fish respond in a cage where they are not free to make any substantial movements in response to the sound. If the fish were not restrained, they might have moved away from or toward the sound or not moved at all. This is not known, but the important point is that the behavior in this test tank or in any restrained enclosure (even if very large) does not provide insight as to how animals will behave in their normal habitats.

The only useful studies on the effects of sound on fish behavior must be done with field observations where the movement of fish can be observed and quantified before, during and for an extended period after exposure to sounds. By their very nature, these are very difficult studies. The closest to this kind of study was done by Wardle *et al.* (2001), where they were able to use video observations to watch the movements of fish and invertebrates in a small reef area off Scotland during presentation of sounds from a seismic air gun. Similar studies are needed, but even these studies are only useful for animals that stay in a single location (e.g. on a Scottish reef). What is equally important are observations of the movement of fish such as Atlantic cod, herring, and other commercially important species over large areas in deeper water. To date, the only small-scale study of this type was done using sonar (Slotte *et al.* 2004). However, sonar is not necessarily the most effective means to observe fish behavior because the sonars that can differentiate species and individual animals are limited to observing animals at only several hundred meters from the sonar device. As a consequence, such sonars will not work with fish that move over large areas unless the sonar vessel follows the fish, and the vessel itself might alter fish behavior.

A related and interesting issue is whether the sounds of research or fishing vessels have any impact on fish behavior. This is a rather controversial subject, but there is some evidence that suggests that this might be the case (e.g. Mitson 1995; Handegard *et al.* 2003; Mitson & Knudsen 2003), although other data suggest less of an effect of quieted ships (e.g. Ona *et al.* 2007; De Robertis *et al.* 2008). Therefore, studying responses of fish from a vessel might provide results that do not reflect the fish behavior that would occur if the vessel were not present.

FINAL THOUGHTS

To date, the concerns regarding the effects of increased background sound on fish far exceed the extent of data that is available to support such concerns. Although there is little doubt that increases in sound are likely to affect fish, we are far from understanding the extent of these effects and even further from being able to provide useful models that will enable us to predict such effects.

Moreover, although the data on which this review is written emphasize juvenile or adult fish, there are valid concerns that the effects might vary not only as related to genetic stock and/or developmental history, but also on the basis of fish size and particularly with young animals (Yelverton *et al.* 1975). There is also the concern that sounds might have some level of impact on eggs and larvae. However, data related to eggs and larvae are, if anything, even less extensive and more equivocal than for juveniles and adults because studies have often been undertaken in small chambers or by using mechanical rather than acoustic signals.

The "bottom line" is that to really understand if and how sound affects fish, we need a considerably larger body of carefully derived data that looks at diverse species and sound sources. At the same time, because it is not possible to investigate effects for every possible exposed species, there needs to be a limited number of species studies that can, in some way, serve as representatives for others. These would be selected based on hearing capabilities and other anatomical, physiological and ecological characteristics that would enable a broad sampling of fish "types." In addition, although many different sound types can be examined (e.g. pile driving and air guns), it is not really feasible to test all characteristics of the sounds, such as repetition rate and level, on all representative species. Therefore, it will become necessary to select a careful suite of sound parameters that will facilitate understanding other characteristics.

The significance of acoustic particle motion in developing metrics that correlate with effects also needs to be resolved as soon as possible. Some studies are reporting acoustic particle velocity in addition to sound pressure levels; however, no correlations between the observed effects and particle motion have been developed. If excess particle motion significantly contributes to hearing loss and/or tissue damage, as we believe it does, then particle motion will need to be considered in risk analyses and assessments when planning sound-producing activities in the marine environment.

Finally, methods must be developed that will allow for studies of behavior of "wild" animals that are not restrained in any way that examine their response, both short term and long term, to exposure to different sounds.

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