Fish, Mollusks and other Sea Animals' use of Sound, and the Impact of Anthropogenic Noise in the Marine Acoustic Environment

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Many marine animals use sound and acoustic energy sensors to adapt to their environment. Most biological studies closely examine a particular species' relationship to a specific stimulus. This report examines the fields of research on marine biological adaptations to sound since 1950, assembling an overview of the biological importance of sound in the ocean. It also examines the various sources of anthropogenic noise in the sea with a focus on the potential impacts of that noise on the marine acoustic environment.

1.0 Overview

It has long been known that ocean creatures produce and use sound. Recognition of the musicality of sea animals dates back at least as far as the 7th Century B.C., when dolphins rescued Greek musician Arion from the sea because they recognized him as a kindred musician. Throughout all cultures, the earliest tales of seafaring include accounts of singing sirens, howling serpents and other noisy denizens that inhabit the deep.

Perhaps these tall tales were dismissed by those on the shore as madness induced by sailor's long and lonely stretches over the silent seas, because it was only during the Second World War when sonar surveillance of enemy submarines became critical to national security that the danger of underwater noise produced by fish became apparent.[1] When hydrophones were placed in coastal waters to listen for submarine traffic, they were overcome by all manner of strange noises. If the Navy was going to be safe from enemy submarines, animal noises would need to be identified and distinguished from the noises produced by the subs.

In the sixty years between WWII and the present, much work has been done to identify and qualify the marine acoustic environment – but due to the expense of underwater research, this research has largely been driven by military or industrial concerns. This has left many gaps in our understanding of how marine animals use sound. As we learn more how human survival is dependant on the health of the planet, we realize that a greater understanding of the effect of underwater sound in the oceans is needed. With the increased use of the marine acoustic environment by the military and industry, it seems that it is not so much the safety of our Navy, but the viability of our marine fisheries that is now at risk.

The 'background' noises that we took for granted as some indication of marine life are increasingly being re-evaluated as the necessary sounds of animal survival – sounds that sea creatures use to communicate, navigate, hunt, bond and breed. This perspective has been most apparent in whales and dolphins due to the natural human empathy for these intelligent, air-breathing creatures. It has also been obviated by the catastrophic events caused by interfering with their sound perceptions.[2] The relationship that fish and other sea animals have with sound is less understood. There are many reasons for this: we don't often experience these animals in their environment – they are not as large or interactive with humans as some whales and dolphins are; encounters with these animals and determination of the vitality of their populations have been largely anecdotal and dependant on 'fisherman's luck'; and human familiarity with most sea animals ends at the dinner plate.

With all of the vagaries of fish stock vitality, it would be hard to determine what impact anthropogenic noise has on it, particularly with all of the other factors that stress or compromise ocean life. A thinning population of any species can be attributed to over-fishing, unusual weather conditions, bad fisheries management, water pollution, wetlands depletion, or just bad fishing luck. We can never know when a catastrophic event decimates a fish population because the victims just decompose and sink to the bottom, never to be seen; and in order to determine the long term affects of a compromised environment, we need to evaluate trends over years. In light of this, if we want to maintain the viability of marine fish stocks, we need to carefully consider the possible risks of any action that impacts their environment, including the impact of anthropogenic sound.

This report will consider the known relationships that various ocean animals have with sound, and their dependence on sound perception. It will also consider how various ocean animals are affected by ocean noise caused by human activities such as industrial, military and commercial exploitation of the sea.

2.0 Sound in the ocean.

Most people consider the ocean a silent place. This is largely due to the fact that humans are poorly adapted for underwater sound. We typically consider air a necessary component to sound generation because it is air that sets our vocal cords in motion, producing the sound of our voice. Air is a scarce commodity underwater, and while the whale songs we are familiar with are easy to understand knowing that these animals breathe air, most whales and dolphins don't expel air for their vocalizations. (In many cases, we really don't know how most whales and dolphins vocalize underwater.)

Another reason we believe that the ocean is silent is that our own ears (which are also poorly adapted to hear underwater) are not obvious appendages on sea animals. The assumption is that if an animal doesn't have some form of sound gathering attachments on the sides of their head, they don't have well developed ears. This assumption is reinforced by the fact that when we dive underwater; our delicate ears shut down under the water pressure. We can hear, but the sound is muffled.

Due to these human perspectives on sound and hearing, our natural assumption is that sound is a terrestrial animal adaptation – better suited to lions and birds than to fish and crabs. We assume that fish and other sea animals rely on sight and smell for their perceptual connection to their surroundings.

The truth about underwater sight is that the ocean environment yields poor visual clarity. Unless the water is devoid of life, it will be clouded by plankton and microorganisms. Even the clearest waters rarely yield a visibility of one hundred feet at the surface. And once you descend to a few hundred feet in depth the water above absorbs all sunlight, so it is dark even during the day. As it happens though, sound actually works very well underwater, so in lieu of sophisticated organs of sight and light perception, many sea animals rely on very sophisticated organs of hearing and sound perception.

Perception is a creature's method of sensing environmental properties, translating them to neural impulses, and then further converting the neural impulses into adaptive action. Because sound is a mechanical conveyance of energy, it impinges on the environment in many subtle and complex ways. Sound, or acoustical energy is a pressure gradient over time in a medium – an energy that sets molecules in motion on a specific axis. This energy can be an impulse, an oscillation or a combination of these two. Once the molecules compress, or move, they tend to relax back into their original position. The net affect is that acoustical energy doesn't actually displace anything, only the energy moves. (For a more thorough treatment of underwater acoustics, see Appendix A.)

From the perspective of the organism, this movement of energy can be sensed as a dynamic change in pressure gradients, an oscillation of particles, or a vibration of the medium. Sea animals have many different ways of sensing these properties, and many more adaptive responses to what they sense. To reveal the diversity of sensing methods, we will examine some aspects of the ocean's acoustic environment.

3.0 The Ocean's Acoustic Environment

There are many sources of sound and noise in the ocean; naturally occurring noises that have been part of our planet since the birth of the sea, and anthropogenic noises that date back to the first seafaring people and have been increasing exponentially over the last 100 years.

Naturally occurring environmental noises include the sound of wind and waves, tides and currents, weather, tectonic and volcanic activity, as well as all of the sounds produced by ocean animals. Anthropogenic noises include the sound of watercraft (from jet skis to supertankers); offshore oil/gas exploration and production noise; sonar – especially military high-power equipment; underwater telemetry and communication for mineral exploration and research; fish 'bombing' and other underwater explosives; civil engineering projects, and overflying aircraft. [3]

3.1 Naturally occurring, non-biological ambient noise

Even devoid of life, the ocean is not a silent place. Wave action, wind and rain on the surface create a background din that ranges between 40dB – 70dB SPL (re: 1μPa)[4] in deep water, and up to 90dB in shallow coastal areas. Other non-biological sources of sound include geological sounds that can add significantly to the ocean ambient noise.[5]

In polar regions the shifting ice packs – melting, cracking and breaking away, and the tidal surge under broken ice fields – creates an incredible cacophony of noise.[6] The ambient noise due to ice action may be as high as 90dB throughout the year. The sounds of weather on the ocean are variable and transitory; rain and hail hitting the ocean surface, lightening, thunder and the ever-present winds occur throughout the seas, moving across the globe. Regional sound sources include the sounds of tides and currents. Tidal flows are periodic and currents are more constant, but as water in motion moves across the submarine terrain – from sea mounts to kelp beds – sounds are produced that are akin to the sounds produced by wind over land.

Tides and currents interacting with sea bottom features, the seabed, river deltas and estuaries create unique soundscapes that are geographically specific. (Sounds from the tidal swings in New Foundland are as unique to that area as are the deep sounds of the Humboldt Current to its course.)

Volcanic activities such as deep hydrothermal venting or volcanic eruptions are geographically specific and can be a continuous source of sound in some areas. Seismic events – either the sudden or gradual sifting of tectonic plates – adds to the cacophony, creating an ocean soundscape that is rich and varied, and unique to their locations. The geographic specificity of noise sources is an important feature to ocean biology because it has been surmised that certain whales may navigate by recognizing acoustic features of ocean geography[7].

3.2 Naturally occurring, biological ambient noise

Of the many sources of biological noise in the ocean, we are probably most familiar with the songs of whales and dolphins, but there are countless other sources of biological noise in the sea. Various fish grunt, grind, sing or scrape to produce sounds for territory, bonding, and hunting purposes. Many crustaceans are adapted to sound making in way as diverse as their terrestrial insect cousins. Even the sounds made by barnacles when opening and closing, and by the movement of their appendages can be picked up for many miles from barnacle beds.[8] In tropical and semitropical coastal regions, the dominant biological sound is the crackle and hiss of Snapping or Pistol Shrimp (*Cragnon, Alpheus and Synalpheus*). These shrimp stun their prey with a loud report from claw-trigger mechanism. Their sound is so predominant in these latitudes that placing a hydrophone underwater in their habitat sounds like placing a hydrophone in a glass of champagne. The ambient noise level attributed to these creatures can exceed 70 dB.[9]

Until recently, biological sounds only came into question when they somehow interfered with human activity – when the humming of ‘Harbor Midshipman’ (*Poricthys*) made life in a marina hard to bear, or when the noise of Croakers (*Sciaenidae*) and Sea Robins (*Triglidae)* interfered with sonar surveillance. Since 1990 and the end of the ‘Cold War’ some of the expensive and confidential military technologies became available to industry and research, and with it a deeper inquiry into the sources of animal sounds in the sea. With these tools the rich and varied biological soundscapes of the sea began to emerge: schools of singing fish; mysterious tapping, humming and oscillations; long distance sounding of whales; pops, chortles, grunts, bells and bangs. It is over this naturally occurring acoustical ambience that sea creatures of all species live, hunt, bond, procreate and die.

4.0 Sea Animals and Sound

The animals considered in this report do not represent all ‘sound specialist’ animals in the sea. Animals discussed herein were chosen because of the available information on them, and because of their commercial and apparent environmental importance.

Whales and dolphins are considered briefly in this report because there is more common knowledge about these creatures’ relationship to sound than any other class of sea animal. They are included as a touchstone for our common knowledge, but even with the body of knowledge about cetaceans and their sound perception, it is clear that we actually know very little about how they use sound. This sets the broader perspective that while considerable efforts are being made to understand the auditory perception of sea animals, our understanding is miniscule compared to the vast diversity of sea animals and their adaptations to sound.

The inquiry into fish is farther reaching because this class includes so many species with so many different ways they use sound for survival. The inquiry into mollusks is scant due to the scarcity of research on molluscan senses. This is also the case with the crustaceans – shrimp, crabs and lobsters, and Cnidaria – jellyfish, anemones and hydroid plankton. These last are included herein because their primitive organs of motion sensing, balance and location are considered the early adaptations of what has become the vertebrate ear.[10]

Wavelength, frequency, period and decibels are all abstractions to sea creatures; their only concern with sound and acoustical energy is in how this energy impinges on their organs of perception, and that they can adapt to it in order to survive. Survival means different things to different animals: to a Grouper it involves setting territorial boundaries; to a Sea Robin or Midshipman it involves community and breeding relationships; to the Tuna it involves synchronization to the swimming patterns of the school, and perhaps navigation; to Anchovies it involves evasion from predators; to clams and scallops it involves sensing currents for food and threat evasion.

All of these different uses of sound are activated through various sense organs. Some have common structural analogies to mammals – such as the neuromasts on the lateral line of fish and the same nerve structures in mammalian cochlea; others are unique to the creatures, such as the statocysts in mollusks and cnidaria, or swim bladders in fish. In any event it is clear that most sea animals have a biological dependence on sound and acoustical energy. This fact should yield a rich vein of information as we develop the tools, the language and the understanding to explore their secrets of sound perception.

4.1 Marine Mammals – Whales and Dolphins

People are quite familiar with the sounds of whales and dolphins. It is not the purpose of this report to reiterate this common knowledge. Suffice it to say that it is generally known that cetaceans communicate and navigate with sounds. It is also fairly common knowledge that dolphins and porpoises use sonar to echolocate and distinguish things in the water. Some dolphins and whales also use loud noises to stun their prey.

The hearing mechanisms of various whales and dolphins are only partially understood. While these animals do have the inner ear mechanisms of other mammals – the cochlea, tympanic membrane and approximation of semicircular canals, there is some informed conjecture that these animals have other organs of sound perception. The 'melon' of some odontocetes is generally assumed to be an acoustic organ, the trigeminal nerves in mysticetes and other enervation around the skull may serve as acoustic sensors. Various cavities in the bodies of whales may serve as pressure sensors. The studies continue.

4.2 Fish – Teleost (bony fishes) and Elasmobranches (Sharks and Rays)

Heretofore the study of sound perception in fish has divided this class of animal into two camps; those that are 'sound specialists' and those that are 'sound generalists'. Some of the distinctions between these groups arise around whether the animal has a method of producing sound, and how complex their known organs of sound perception are. These qualifications have served as general guidelines for the inquiry; but the question that keeps the door open for further exploration – and continues to erode the distinction – is "Why do sound generalists need to have a relationship with sound anyway?" As a result, the specialist/generalist distinction is rapidly becoming obsolete, as we learn some of the ways various fish use sound in their environment.

Perhaps most intriguing to this is the recent consideration that ambient noise in the ocean may actually serve as a source of 'acoustic illumination', similar to how daylight illuminates objects we see. The theory is that objects and features in water cast acoustic shadows and reflections of ambient noise that fish can perceive and integrate into the perception of their surroundings.[11, 12] This has far reaching implications for the distinction of how fish and other animals use sound in the sea, and muddies up the distinction between the sound specialist and sound generalist groups.

There are some common adaptations to various environments by fish. Those that live in estuaries or muddy environments often have distinct methods to perceive that environment. This often includes the ability to produce sound and mechanical sensors that facilitate the perception of the sound they produce. However, fish that do not live in muddy water may also have these same sensing organs – even if they don't produce sound. There are organs in some fish that sense water pressure due to depth that also sense pressure gradients due to acoustical energy. Some fish have sense organs that are extremely sensitive to subtle particle and impulse motion – organs that work even in strong currents while the fish is moving. From a physical/mechanical standpoint, their swimming should overload the sensitivity of the organs. From this we could surmise that these fish have some complex ways of integrating motion stimulus that might be akin to our being able to hear a mouse whisper while driving on the freeway.[13]

One challenge in determining what a fish – or any animal hears, is the bluntness of the available testing procedures. Most audition tests are based on the Skinnerian model of behavioral research. This involves cultivating recognizable responses to specific stimulus. The researcher either rewards or punishes an animal coincidently with the appropriate stimulus – sound in the case of audition testing. The animal is trained thoroughly enough so that their willful response to the stimulus becomes apparent. When the stimulus is modified in some manner, the relationship between the modification and the original training stimulus can be established. Problems arise when dual thresholds are found.[14] This condition might indicate a shift from one hearing mechanism to another – such as a shift from swim bladder to lateral line sense, or a shift from pressure to particle velocity perception, or even a shift from a voluntary to an autonomic nervous system response that somehow co-stimulates a voluntary response. Even stimulus/response testing that induces autonomic responses could be subject to similar response threshold shifts.[15]

Most audiograms of fishes indicate a low threshold (higher sensitivity) to sounds within the 100 Hz – 2 kHz range. This narrow bandwidth could be due to mechanical limitations of the sense organs, or physical constraints of the testing systems.[16] If the acoustic illumination theory proves correct, it could account for a high frequency response that is not anywhere in the realm of a voluntary stimulus/response modality. It could indicate a response mode akin to training a fish to seek food when a bell rings, and then expecting the same fish to seek food when you put blue sunglasses on it.

The difficulty in unraveling many of these mysteries lies in the simple fact that while we may be able to invoke repeatable and observable responses in some fish, we will never be able to figure out what they perceive. To paraphrase an axiom of cognitive science: “If a fish could talk we wouldn’t understand what it was trying to say.”[17] We can look at the physiology, environment and social setting of various creatures and surmise how they use the stimuli of their surroundings, but even our most basic understandings depend on perceptual assumptions that we humans can grasp.

In light of this, the best we can do is continue to explore the many organs of perception that fish use, examine their behavioral responses to acoustic stimulus, and attempt to open our windows of understanding to include broader slices of time, larger frequency spectra, and wider dynamic ranges.

4.2.1 The Sound Organs of Fishes

Probably the most distinct organ associated with fish aside from their gills is the ‘swim bladder’. This organ serves many purposes. Its most basic function is to serve as a hydrostatic regulator, allowing the fish to mediate buoyancy and equalize internal and external pressures. In some fish such as the Grunts (*Pomadasyidae*) this bladder is also used as a resonator to amplify the grunting sounds they make by grinding their pharyngeal teeth. Other fish such as Drums and Croakers (*Sciaenidae*) have special muscles attached to an elaborate swim bladder to produce sound for navigation and maintain contact with their school in the heavily silted estuaries in which they live.[18]

Many fish have a mechanism of small bones called 'Weberian ossicles' that fasten to the swim bladder and transfer vibrating energy from the bladder to the labyrinth of the inner ear. This structure has a kinship to mammalian middle and inner ear structures. The analogies are between the swim bladder and the tympanum; the Weberian ossicles with the hammer/anvil/stapes; and the labyrinth with the cochlea and semi-circular canals.[19] The weberian ossicles of fish typically comprise four, rather than the three bones in the mammal middle ear, and the labyrinth appears a bit more complex in fish than in the human inner ear. This may be due to the fish's need to sense rotational and linear acceleration, and bathymetric stimuli with more acuity than terrestrial animals, as well as their need to perceive the seismic, gravity and sound stimuli that terrestrial animals also require.

Fish also have structures within their labyrinth called 'otoliths.' Larger than the 'otoconia' of other vertebrates, they are concentrations of calcium salts suspended in a sensory envelope of gelatinous membrane.[20] Because of the location and orientation of the otolith organs in the labyrinth, it is tempting to assume that they are somehow associated with orientation and vectors, though they seem to be more associated with particle motion sensitivity (see **Appendix A1.2** below) and in some cases pressure gradient sensors.[21]

Because of the physical properties of a swim bladder, its contribution to audition involves pressure gradient sensing. This is in terms of both comparative hydrostatic sensing, as well as sensing the more rapid changes or oscillations of pressure gradients – i.e. acoustical energy. This capability would allow fish to sense long distance sound generation and ambient noise by way of this organ. Not all fish have swim bladders; bottom dwelling fish such as sole or halibut don't have swim bladders.[22] In lieu of this, their sound perception abilities derive from cilia, or hair cells located on the upper surface of their body. These cilia are located in various concentrations on the bodies of all teleost fish, but most particularly, they concentrate in the form of a lateral line that runs parallel to the spine. It could be surmised that the cilia distributed over the body are predominantly current flow sensors, and the lateral line is more of a frequency discriminating particle motion sensor.

The similarities of lateral line enervation to the human cochlea is an environmental adaptation that gives us clues to how some fish may discriminate sound.[23] While there is a general agreement that the lateral line does serve as a mechanoreceptor, there continues to be some discussion about its true function. The broader view is that it serves in one or more of the capacities to sense water movement (distance touch), surface waves (frequency dependant particle acceleration), or low frequency sound (pressure gradients).[24]

While there is unambiguous evidence supporting all three modes, there remains confusion as to how an organ that can sense pseudo-random displacement from locally generated currents and water movement [25] can also simultaneously discriminate frequency dependant acceleration, oscillating pressure gradients,[26] and the direction of the sound source.[27] The general assumptions are that certain fish have overlapping receptors that allow them to perceive or distinguish various qualities of acoustic stimuli.

All of these aforementioned perceptual modes are characteristics of various species which allow them to perceptually lock into their surroundings with acoustic adaptations particular to their species – for hunting, territory, bonding, spatial orientation, navigation, predator aversion, etc. An inquiry more specific to the vitality of fisheries involves how schooling fish – tuna and herring for example – use the acoustic energy generated by their school to keep them connected with each other. Evidence suggests that the lateral line as a pressure gradient and particle motion sensor enables schooling fish to mediate their proximity and velocity within the body of the school. [28,29] One inference that could be drawn from this is that a school could be modeled as a low frequency oscillating body that the individual fish synchronize to. This view is supported by schools that 'flash' simultaneously as they respond to threats. This is also substantiated by evidence that when startled by very loud noise (air guns), schooling fish fall out of rank and take some time to re-assemble.[30] This 'startle' response does involve establishing a tighter grouping, so the response is not a scatter response. The interruption – or startle response – observed in the air gun study might indicate that the hearing process of each individual fish is momentarily compromised, or the pressure gradient field of the school loses integrity and takes some time to resettle, or perhaps a bit of both.

Fish colonies in stationary habitats also need to establish and maintain contact with their co-species. In these cases they can't rely on the low frequency pressure gradients generated by swimming bodies because the fish in these colonies may be largely sedentary. Rock Fish, Grouper and Toadfish all dwell in areas often concealed by rock caves, thick kelp or muddy water. All of these animals 'vocalize' by way of their swim bladders coupled with muscles or other mechanical means of sound generation. The 'Midshipman' in the Toadfish family is probably the most known for their long, low frequency humming. They often dwell in shallow bays and their humming is heard through the hulls of nearby boats. While each animal has a hum fundamental frequency of 80 – 100 Hz, the colony will set up infrasonic beat frequencies of 0 – 8 Hz. These animals have an ability to discriminate these beat frequencies.[31] This ability probably has something to do with maintaining identity and contact with their colony.

Elasmobranches – sharks, skates and rays – rely on low frequency sound to locate distressed prey. While sharks do have refined electro-chemical receptors, a research diver noticed the immediate appearance of sharks upon spearing a food fish, even while the prevailing currents did not favor the dispersal of blood in the shark's direction.[32] His further inquiry established a relationship between low frequency sound and other behavior, including aversion behavior associated with rapid increases in low frequency sound levels by 15 to 20 dB – a change in levels that alerted the sharks about unexpected phenomena.[33]

Evidence presented here indicates that fish as a class have very complex and diverse relationships with sound and acoustic energy.[34] The complex hearing mechanisms of fishes, and fish audition are rich fields of inquiry that are sure to challenge our assumptions and yield fantastic results as we explore further.

4.3 Mollusks – Clams, Mussels, Oysters, Squid and Octopi

Probably the most challenging aspect of the study of sound sensitivity in mollusks involves the sustained belief that these animals are far too primitive to have significant communication systems. A complication with the evaluation of marine invertebrates' response to sound is that their reaction time scales are significantly different than human time scales. Our identification with birds, fish and mammals devolves around their being symmetrically structured vertebrates (two eyes, two fins, hands or wings, etc.,) and that their response time is more closely aligned to human stimulation/response behavior.

'Hearing' is not really discussed when speaking about invertebrate sound perception because by and large these animals do not have the type of nervous system that vertebrates have. When speaking of invertebrate physiology, the term 'phonoreception' is more appropriate when describing an organ or mechanism that responds to acoustic energy. These organs may be a hybridization of gravity, orientation and hydrostatic sensors, or specific mechanisms that answer unique survival adaptations to acoustic energy by each organism.

The mollusks reviewed herein include clams, oysters and mussels, snails and slugs, and squid and octopi. The inclusion of squid and octopi with other mollusks may seem counter-intuitive because we have learned that these highly mobile animals demonstrate perceptual modes that are identified with observable intelligence. This observation may actually be due more to framing them in an anthropomorphized time context rather than a lack of perceptual abilities on the part of less mobile, or slower species of this phylum. That being said, we do know that octopi have a highly adaptive intelligence that goes beyond mere pattern recognition to a degree of associative reasoning and problem solving (or problem causing, by the accounts of some aquarists). Interestingly enough, octopus species have not demonstrated an adaptation to even rudimentary sound perception.[35]

Squid, on the other hand, have demonstrated responses to sound. This may have something to do with their schooling nature that requires synchronization with the school, and predator aversion perception akin to that of schooling fishes. Research on squid audition is currently scant. Only the bluntest studies seem to have generated funding – studies of destructive noise levels and startle responses. We know from these studies that squid are adapted to particle and pressure gradient acoustic energy. The current belief is that they hear by way of statocysts,[36] or possibly by proprioception – the sensing of sympathetic movement of muscles and tissues in the body acted on by acoustic energy.

While researchers noticed a predictable startle response at 174 dB (firing of ink sacks and avoidance behavior) from instantaneous impact noise, a ramped noise indicted a response threshold of 156 dB by way of a noticeable increase in alarm behavior – an increase in swimming speed and presumed shifts in metabolic rates. The squid's response to ramped noise also includes their rising toward the surface where an acoustical shadow of 12 dB occurs. This would indicate an annoyance sensitivity of perhaps 144 dB.[37]

Little is known about squid hearing, but even less is known about Lamellibranches (bivalves such as clams and muscles) and Gastropods (snails, slugs and limpets). Any acoustic response in these is typically measured by aggravation response – a study that successfully used ultrasound to eradicate zebra muscles,[38] for example. Given that the purpose of this study was aimed at killing these creatures, threshold auditory levels were not revealed. It would be hard to determine if it was an aversion to noise or some other physical action that killed these animals.

The marine lamellibranch, *Glossus humanus* or Ox-Heart Clam, has demonstrated a remarkable sensitivity to vibrations well below what would be considered a 'shock wave'. That their heightened sensitivity might be used for something other than escaping predators is shown by the studies of surf clam tidal migrations. On the incoming tide, the breaking waves cause the clams to rise to the surface and be carried in with the waves. These animals would need to be able to sense the shifting of the tides in various surf patterns to determine when to cast loose and let themselves be cast up to the tide lines. (When research biologists stamped their feet on the wet sand, these clams would hurriedly rise to the surface.[39])

In gastropods, some animals that do not respond to wave or particle motion in the water will none-the-less respond to substrate-borne vibration on the surface of what they are perched on. This might indicate that they are directly coupled through their foot to the bottom, sensing vibration through proprioceptors in their muscles. If this is the case, seismic motion may have a strong affect on them that waterborne sounds would not. This substrate vibration sensing may serve for rudimentary predator detection, or as sophisticated as community identification and bonding sense. The scraping radula that these creatures use for eating would set up vibrations in the substrate that may serve to keep these creatures in their colonies.

While some of the sound perception modes of mollusks discussed herein may seem speculative, these conjectures are not beyond reason. Hopefully, they will serve as steps toward the understanding of how and why various mollusks respond to sound.

4.4 Crustaceans – Shrimp, Krill, Lobsters and Crab

Crustaceans could be considered as 'insects of the sea.' Like their terrestrial cousins, they have exoskeletons and segmented appendages, many live in communities that school or 'swarm' like insects, and many make noises akin to the buzzing, chirping, clicking and singing of crickets, cicadas, mosquitoes and beetles. Crustaceans that do not specifically make noise none-the-less respond to acoustical cues. Many animals that do not seem to communicate by way of sound are suspended in the 'collective' sound of their school – synchronizing their movements in response to the body of the school as previously mentioned in schooling fish and squid.

Crustaceans and insects do not have ears, bladders or lateral lines, but they possess chordotonal organs. These organs appear at the joint segments and are internal mechanoreceptors. As such they serve as proprioceptors, or as highly specific mechanoreceptor organs – e.g. hearing organs.[40,41]

Chordotonal organs account for the acoustical sensitivity of fiddler crabs (*Uca pugilator*), hermit crabs (*Pagurus*), and other small tidal crustaceans. Many of these animals are sound sensitive to predators from both in and out of the water. They also use sound cues to scavenge their food. An associate in Queensland related how the Aboriginals in his homeland would call the crabs out of hiding by mimicking the sound of crabs eating. The crabs would hear 'feeding' and come out to investigate, at which point the callers would pluck the crabs off the rocks for dinner. The complexity of sound perception in these tidal animals is indicated by their ability to distinguish survival sounds from the ambient sounds of waves and surf. The ability to discriminate the sound of predators' footfalls from the sound of water splashes, from the sound of scampering prey all in a din of tidal backwash would require a fairly sophisticated auditory signal processing ability.

Deeper water scavengers also use sound cues to hear food as it falls to the sea floor. Studies indicate that sensitivity to 'micro-seismic' events in the frequency range of 30Hz – 250Hz enables deep-water scavengers to detect food-fall to distances of 100 meters.[42] These deep-water animals also require sensitivity to the sounds of predators. The adaptation of animals to sounds of threat is indicated in the recent anecdotal evidence that schools of pelagic shrimp have adapted evasion strategies to the sound of shrimp trawlers. When the trawlers circle in, the shrimp dive deep, below the nets.

We typically don't associate the scampering claws or the bubbling noises of tidal crabs as 'deliberate sound,' just as we don't consider the swimming noises of pelagic shrimp or schooling fish as 'deliberate,' though these sounds are significant elements of the creatures' survival. They are not 'words,' but if you spend any time in a tidal mudflat, the "snap, crackle and pop" of crustaceans clearly signals the existence of living organisms in their environment – useful information to any organism dependant on that environment.

In 70% of the world's coastal areas, the dominant crackle of snapping or pistol shrimp speaks for itself about the biological importance of the noise. That these creatures use sound as a hunting tool seems remarkable enough; continuing the inquiry into whether the shrimp use this sound to maintain contact with other snapping shrimp – i.e. for communication – boarders extraordinary: Could the acoustic illumination principles mentioned above be used by the shrimp themselves? Signal coherency of their snapping may give clues to whether they coordinate their snapping with the acoustic community, or just snap randomly.[43] While studies are still in progress, this characteristic would not be dissimilar from how the sound of individual crickets and cicadas is mediated by the sound of the community, creating the pulsing and humming choruses of terrestrial summer nights.

Spiny lobsters have comb-like rasps on their antennae that the scrape on the tops of their shells in a manner akin to crickets' scraping of the comb-like rasp on their elytra together to produce sounds.[44] In lobsters, this sound is presumed to be gender and breeding associated because the male lobsters become agitated when this sound is played back to them.[45] Similar gender associated sound generation also plays role in the acoustic life of the fiddler crabs (*Uca pugilator*),[46] although the mechanism of sound generation is by way of their singularly large claw.

We are just beginning to listen for and hear the myriad of sounds used and generated by marine crustaceans. By deeper inquiry and understanding, we may be able to employ some of their methods of sound communication, adapting our uses of ocean acoustics to their highly evolved adaptations to the marine environment.

4.5 Cnidaria – Jellyfish, Anemones, Hydra and Corals

This phylum of marine invertebrates includes jellyfish, anemones, hydra and corals. Understanding of the sense organ of these animals is only rudimentary, which is probably due to the fact that as specimens, most of these animals are physiologically simple, lending themselves to the lowly role of student biology dissecting practice. The perceived economic usefulness of Cnidaria generally ends here.

What this understanding does reveal though is the presence of statocyst organs in some of these creatures. These organs consist of a calcareous ‘statolith’ in an enervated envelope, considered to be organs of equilibrium; gravity acting on the statocyst allows the organism to orient. This mechanism is considered an early adaptation of the organs of balance in mammal inner ears. Because it is found in creatures with ancient evolutionary history and is so simple in form, statocysts may have been the first sense organ developed in multi-cellular animals.[47]

One mystery that may cue us in on reasons to explore broader bandwidth of the Cnidaria statocyst involves how these creatures navigate. Many of these ‘free floating’ creatures have annual migrations that circumnavigate large areas in the oceans. Their migrations are largely unseen as a pattern because of their slow underwater course. Fishermen or researchers will only come upon them in migrating colonies during particular seasons. In one case, the ‘By-the-wind Sailor’ *Valella valella*, lives in large migrating colonies that have an annular migration path. The Valella do not have statocysts, but must have some other organs of mechanical energy perception. They use an ‘s’ curved sail to propel themselves through their journey in large rafts floating on the ocean surface, body to body. Each individual organism sets its sail angle by adjusting against the body of the colony, and thus most of the colony avoids blowing ashore even in coastal areas that are dominated by onshore winds. (The ones that do break away are seen on beaches at specific times of the year.) The valella need to establish angular relationships to the prevailing winds in order to sail in the proper direction. Can they also integrate the angles and the rhythmic undulations of the swells to help them know where they are?

While it is possible that the individual organism does not have phonoreceptors or other mechanoreceptors that can be monitored within the organism, the entire raft of Valella may somehow constitute a type of ‘super organism’ (as defined by E.O. Wilson), that enables the raft to sense and respond to environmental stimuli that the individual organisms are not equipped to interact with. It is also true that a number of marine planktonic organisms respond to pressure changes by moving up and down in the water column. The hydrostatic receptors that mediate this are still undetermined, but speculations on their nature usually implicate some sort of pneumatic device. If this hypothesis proves true, the animals also have a device suited to sound reception[48] sensitive to low and ultra-low frequency pressure gradient acoustic energy.

One class of cnidaria that does have sound responsive sense organs is the anemone. These creatures have proprioceptors that help them trap their fast swimming prey. Some species have relationships with anemone fish that take up residence in the stinging tentacles of the anemone. Protection of the fish from stinging by the anemones apparently involves special rhythmic movements of the fish that inform the mechanoreceptors of the anemones of their presence, inhibiting the capture response of the anemone.[49] The discussion around anemones includes whether rhythmic stimulation amounts to acoustic perception, or just a "musical" sense. Unfortunately some of the perceptual studies in a lab using mechanical stimulation with glass pipettes may indicate as much about the researchers' patience as it does about the presumed insensitivity of the anemone to subtler stimulation.[50]

The same could be said about corals, in as much as the stimulus response models in the literature seem to focus on mechanical stimulation alone. Corals are responsive to hydrostatic disturbances – particle motion induced by currents, predators and prey. Literature is sparse on the acoustic adaptations of corals, or how they respond to coherent or persistent sound or noise sources.

At present there is still a dearth of research and understanding about how Cnidaria – with their ancient evolutionary history – actually perceive and adapt to their environment through acoustic energy and vibration, and how this has enabled them to survive over the eons despite their 'simplicity.'

5.0 Summary of Animal Sound Perception and Production Modes

From the preceding it is clear that many sea animals use sound in a variety of ways. Some animals use sound passively, others actively. Passive use of sound occurs when the animal does not create the sound that it senses, but responds to environmental and ambient sounds. These uses include:

1. Detection of predators.
2. Location and detection of prey.
3. Proximity perception of co-species in school, raft or colony.
4. Navigation – either local or global.
5. Perception of changing environmental conditions such as seismic movement, tides and currents.
6. Detection of food sources and feeding of other animals.
7. "Acoustic illumination" akin to daylight vision.

Active uses of sound occurs when the animal creates a sound to interact with their environment or other animals in it. Active uses include:

1. Sonic communication with co-species for breeding.
2. Sonic communication with co-species for feeding, including notification and guidance of others to food sources.
3. Territorial and social relations.
4. Echolocation.
5. Stunning and apprehending prey.
6. Alarm calls used to notify other creatures of the approach of enemies.
7. Long distance navigation and mapping.
8. Use of sound as a defense against predators.
9. Use of sound when seized by a predator (perhaps to startle the predator.)

The methods of sound production are as varied as the uses. Some methods are still not entirely understood, but they include:

1. Mechanical clacking or rattling of plates or teeth.
2. Grinding or scraping of bones, shells, appendages or teeth.
3. Oscillations of bladders by way of special muscles.
4. Oscillations of the entire body.
5. Distribution of fluids or gasses within the body through sound producing organs
6. Forceful ejection of fluids or gasses outside of the body through sound producing organs or mechanisms.

The sounds produced and/or perceived through these methods can be attributed to pressure gradient and/or particle motion energy. The useful frequency ranges incorporated by these various methods span the range from ‘human infra-sonic’ frequencies of 0.1 Hz through ultrasonic frequencies nearing 300 kHz.

Due to the physics of sound in the sea – and the wavelengths of the various frequencies, the infrasonic frequencies (0.1 Hz – 20 Hz) are probably dominant in long distance navigation, communication, and environmental monitoring. The lower frequencies (1Hz – 100Hz) are likely involved in proximity detection, predator/prey interaction and feeding. The mid frequencies (1000 Hz – 10 kHz) dominate close range communication and ‘communicative’ interaction with other organisms. The higher frequencies (10 kHz – 300 kHz) are likely used for echolocation, acoustic illumination, holophonic imaging, and perhaps co-species communication.

It has not been established that any sound in any frequency range predictably stimulates voluntary, sympathetic, or autonomic responses in any species, e.g., that low to mid frequencies are used exclusively for communication in teleost fishes, or that low frequency impact noise predictably induces startle responses in all squid. It is likely that any sound in any regime could stimulate any, none, or all response modes. It is also possible that certain sounds could stimulate systemic responses that do not fall under the rubric of ‘nervous system response,’ but none-the-less stimulate the system in some fashion – observable or otherwise.

There is much to learn, but with the increasing sophistication of our research tools and breadth of our curiosity, the mysteries of the marine acoustic environment are becoming ever more open to exploration. As we learn more about how various animals have adapted to their ocean surroundings, our understanding will undoubtedly have a positive impact on the quality of our own lives.

6.0 Anthropogenic noise in the Sea

In 1490 Leonardo da Vinci observed how the sound of ships traveled great distances underwater. The sound of ships in the 15th century included the noise of rudders and rigging, oars and the handling of cargo. Seafaring, while not in its infancy, was a “life driven” technology; the power of wind and human muscle generated the only anthropogenic noises in the sea. Over the next 400 years, acoustic technology at sea involved innovations such as underwater bells and whistling buoys on submerged rocks and reefs to warn navigators and captains away from marine hazards. With the advent of steam powered engines, the quality and level of noise began to shift dramatically. With the ability to navigate to, and develop the far reaches of the globe, the use of dynamite and diesel driven pile drivers began transforming the soundscape of coastal waters worldwide.

Once the mechanization of seafaring and coastal civil engineering took hold, ocean noise began increasing exponentially. Over this time there was little scientific inquiry about the sounds of the sea, so the changing profile and density of ocean noise went unnoticed until the strategic value of anthropogenic noise became apparent. In response to the very effective submarine warfare in WWII, after the war the U.S. Navy developed an underwater network of sound gathering hydrophones. The first generation of ocean-bottom listening device arrays were deployed in 1954 - 1955 in a system that eventually was called SOSUS – an acronym for ‘Sound Surveillance System.’[51]

SOSUS was strictly a passive, “listening only” technology. As it developed, the ability to monitor ocean traffic became quite accurate, with the capability of monitoring individual vessels at long distances, determining their position, course, class, and size. Once the ‘Cold War’ ended, SOSUS was made available to research scientists.[52] When military tools for undersea listening were made available to the curious, amazing things were discovered. The perspective had shifted – what had been considered interference became information, and while the diversity of biological sounds became apparent, so too did the incredible din generated by human activity.

6.1 Sources of Anthropogenic Noise – Boats, Ships and Watercraft

In 1992, when the SOSUS program was opened to civilians, researchers got an earful. In addition to being able to hear, locate and track individual whales by way of their vocalizations, for the first time scientists also heard the density of anthropogenic sounds that cluttered the marine soundscape. The most pervasive of these ocean noises were caused by transoceanic shipping traffic. At that time the international ocean cargo fleet included some 75,000 vessels, and the average shipping channel vessel noise level ranged between 70 – 90 dB[53] – as much as 45 dB over the natural ocean ambient noise in the surface regions. In the last 12 years the fleet has swelled to close to 87,000 vessels,[54] and while the mathematical model would only represent an increase of less than 1 decibel to the overall ambient noise, the temporal density and geographic spread increase of 16% over that time more closely represents the equivalent impact of the noise increase.

The ambient noises in an average shipping channel are due to propeller, engine, hull, and navigation noises. Any cargo vessel or tanker will generate 170 – 180 dB of noise at close range; this dissipates over distance through spreading and attenuates as a result of sea surface texture and geometry.

In coastal areas the sounds of cargo and tanker traffic are multiplied by complex reflected paths – scattering and reverberating due to littoral geography. As a result, shipping noise in coastal areas near harbors may easily reach 100 dB, and peak at 150 dB in major ports and seaways.[55] These cargo vessels are also accompanied by all other manner of vessels and watercraft: Commercial and private fishing boats, pleasure craft, personal watercraft (jet skis etc.) as well as coastal industrial vessels, public transport ferries, and shipping safety and security services such as tugs boats, pilot boats, Coast Guard and coastal agency support craft, and of course all varieties of navy ships – from submarines to aircraft carriers.

Every one of these vessels with a motor and a propeller increases the coastal area ambient noise level. Marine engine and drive noise is in the low frequency band of 10 Hz to 2kHz and is typically much louder than the noise of equivalent service terrestrial vehicles. They are louder because for a given drive purpose, the engines are much larger – there is a significantly "higher horsepower per vessel" factor required to just push a hull through water. (Transoceanic vessels have much larger engines than anything found on land.) They are also louder because the ocean environmental law has not stipulated the same muffling devices required for land based vehicles. Additionally, propellers are much louder drive devices than the wheel, and vessels can have as many as eight engine-to-propeller drive systems. Most of these vessels also have various other engines such as cooling pumps and generators which couple noise into the sea through the hull, and through ocean water coupled cooling and exhaust systems.

Most of these vessels also have their own sonar systems for navigation, depth sounding and "fish finding." There are various types of sonars used. A large number of commercial devices operate in the 15 kHz to 200 kHz frequency range with a few watts to a few kilowatts of power.[56] Other locating, positioning and navigational sonars operate in the mid frequency band of 1 kHz to 20 kHz,[57] and yet other long-range sonars operate in the 100 Hz to 3 kHz range. [58] All of these devices operate in an acoustical power range of 150 dB – 215 dB.

Some commercial fishing boats also deploy various "Acoustic Harassment Devices" (AHD's) to ward off seals and dolphins from the easy meals that the fishing boats provide, as well as aversion devices to keep dolphins, seals and turtles from running afoul of the nets. These AHD's include simple explosive devices, pingers and ringers and squeakers that annoy or harass the subject animals – or call them to dinner, by some fishermen's accounts. Explosive devices are somewhat self explanatory – they are either charges set off in the water, or rifle propelled “blanks” to frighten individual animals. Pingers are short duration blast devices that deliver 130 dB pulses of mid frequency noise to startle, but purportedly don’t harm net-predatory dolphins and seals. Ringers and squeakers are significantly louder, emitting 11 to 17 kHz noises at source levels of ~187 – 195dB designed to stun, and thus repel net-predatory mammals.[59] These devices are used around fishing boats, but they are also used in stationary applications around marine aquaculture.[60]

6.2 Non-vessel commercial and industrial noises.

The loudest noises revealed by the SOSUS system were the sounds of marine extraction industries such as oil drilling and mineral mining. The most prevalent and remarkable of these sounds are from the seismic ‘air guns’ used to create, and then read seismic disturbances. These devices generate and direct huge impact noises into the ocean substrate. The tectonic reflections are read to reveal the varied densities of the sea bottom. The noise is directed into the earth, and consequently produces noise throughout the surrounding sea. The peak source levels of these explosions are typically between 250 – 255 dB, though horizontal transmission is more in the range of 200 dB.[61] Air gun impact noise may have repetition rates of one every few seconds and may be heard up to thousands of miles away for hours on end – from each exploration site.

After the ‘exploration stage’ involving air guns, the explored areas need to be exploited. Drilling, coring and dredging performed during extraction generate their own sets of loud noises. There is also a high degree of acoustic telemetry associated with positioning, locating, equipment steering and remotely operated vessel (ROV) control to support extraction operations. Acoustic transponders are well suited for these tasks; they replace vulnerable and costly wire and cable technology, and radio frequency transponders do not work in the ocean. Increasingly sound is used to communicate with well heads, positioners, caps, valves and other hardware. At present there has been little call to keep the noise level down, so acoustic transponder design is driven more by signal reliability and longevity than noise profile. Transponder volumes of 185 – 200 dB at frequencies ranging between 7kHz – 250 kHz are typical, with effective communication ranges of 10 km.[62]

With the exception of the deep water shipping routes, most of this industrial and commercially generated noise happens within the boundaries of the continental shelf. This is where the accessible harvests occur. While this would account for the most noticeable impact on the marine biota, the “up side” is that the physical make-up and conditions of coastal waters provide for a distance-related attenuation rate that is somewhat faster than the spherical spreading factor of 6 dB for every doubling of distance. Factors affecting sound attenuation in littoral areas include relatively shallow waters with a dynamic thermocline, variable bottom geography and composition, and variable and dynamic surface geometry. Depending on the specific conditions, a single 185 dB mid-low frequency noise source may be masked by ambient noise within 100 km (60 miles) or so toward the sea, and perhaps much faster toward the shore. However, it would not be remarkable for this same noise to travel 500km (300 miles.) Of course hearing this single acoustic event presupposes that it is the only event within the subject radius. Increasingly these events are ‘buried’ in the surrounding anthropogenic noise floor before being masked by the natural ambient noise of the sea.

6.3 Research and military communication

Because the ocean transfers sound over long distances so effectively, many schemes have been designed to make use of this feature – from long distance communication, to mapping, to surveillance. In 1991 a group of scientists from nine nations designed a test that sent sounds 18,000 kilometers (11,000 miles) underwater through all of the oceans but the Arctic.[63] Called the Heard Island Feasibility Test (HIFT), this test confirmed that extremely loud sound could be transmitted in the deep-ocean isotherm and could be coherently received throughout the seas. The first program that HIFT spawned was a program designed to map and monitor the deep ocean water temperature. The speed of sound in water is dependent on temperature; this characteristic is used to measure the temperature of the deep water throughout the sea. The theory is that long-term trends in deep-ocean water temperature could give a reliable confirmation of global warming. This program was named Acoustic Thermography of Ocean Climates (ATOC), and after a few false starts due to environmental concerns, the program was authorized in 1996 with two Pacific transmitters; one off Monterrey Bay in California, the other off the island of Kauai. The receivers are stationed throughout the Pacific basin from the Aleutians to Australia. While the 196 dB transmission levels of ATOC are not as loud as the original HIFT program, the transmission schedule spans ten years with 20 minute long transmissions every few hours.

ATOC is a long wavelength, low frequency sound in the 1 Hz – 500 Hz band. It is also the first pervasive deep water sound channel transmission, filling an acoustical niche previously only occupied by deep sounding whales and other deep water creatures.

Concurrent with the development of ATOC the U.S. Navy and other NATO navies have developed other low frequency communications and surveillance systems. Most notable of these is a Low Frequency Active SONAR (LFAS) on a mobile platform, or towed array. Used in conjunction with a towed array of passive sensors called Surveillance Towed Array Sensor System (SURTASS), the entire system acronym is SURTASS/LFAS.

The SURTASS/LFAS signal is comprised of two or more swept tones in the 100 Hz to 500 Hz range. Sweeping these tones across each other creates lower frequency combination tones in the 0.1 to 50 Hz range. These long wavelengths adhere well to the curvature of the globe. In conjunction with the mobile platform, the system will be capable of ensonifying 80% of the world’s oceans. The specified source level of a single transducer is 215 dB – 100 times more powerful than the ATOC signal. However, because the transducer is an array of 18 individual transducers rated at 215 dB, the effective source level is 240 dB. This signal is 55 dB or 320,000 times louder than the ATOC signal.

7.0 Impacts of Anthropogenic Noise on the Sea – Discussion

The difficulty in determining the overall impact of any human activity on the sea is that we are unable to see any immediate affect of the activity on the environment. Aversion by sea creatures, organic stress or even catastrophic damage is hidden in the depths. Our ability to observe long-term trends in fishery vitality involves seasons, years or even decades of circumstantial observations and assumptions about causes. Fishery depletion, which we often assume is caused by over-fishing, may well be caused by other factors. Chemical pollution and destruction of estuary and coastal wetland nursery habitat often figure in discussions about the collapse of once abundant fish stocks. As we learn more about the ocean environment and the creatures that live in it, we will surely find many other elements that constitute a healthy and vital living environment, and what factors compromise that vitality. In consideration of how various creatures adapt to their surroundings through sound perception presented herein, it is probable that anthropogenic noise has greater impact on the ocean environment than we have heretofore understood.

Anthropogenic noise covers the full frequency bandwidth that marine animals use; from 1 Hz – 200 kHz. Anthropogenic noise also occurs throughout the ocean habitats, from coastal inlets and bays, across the continental shelf down into the deep sea, and even into the sea floor. Due to the efficiency of sound transmission in the sea, any noise travels for far great distances and containment is difficult. All human activity in the sea produces noise, and with the exponential growth in ocean resource industries and military use of the sea, that noise is increasingly pervasive.

The information that we have collected over the years on the affects of sound and noise on various marine organisms have largely focused on the more obvious short term responses of living specimens to sound stimuli. The study of marine animals in the lab is far less complicated than habitat observation inasmuch as the complexities of containment and the broad extent of marine environment interactions challenge habitat observations. Lab studies to determine the auditory sensitivity of fish typically involve observing alterations in learned behaviors; auditory studies of mollusks and crustaceans involve aversion strategies or specimen health after a regimen of sound exposure. In many cases, organism acoustical interaction studies involve some measure of temporary or permanent tissue damage.

While tissue damage would be a significant factor in compromising marine organisms, other effects of anthropogenic noise are more pervasive and potentially more damaging to fisheries. Masking – the burying of biologically significant sounds in a noise floor of anthropogenic interference – would compromise all acoustical interactions, from feeding to breeding, to community bonding, to schooling synchronization and all of the more subtle communications between these behaviors. Alternately, anthropogenic sounds that falsely trigger these responses would have animals expend energy without results. Sounds within autonomic response ranges of various organisms may trigger physiological responses that are not environmentally adapted in healthful ways. And lastly, the biological stress induced by higher density acoustic stimulation may be akin to the same biological stresses induced in humans who live in increasingly cacophonous urban environments – triggering or inducing non-survival adaptive responses that damage the organism or damage the community.

Through behavioral and cognitive science, we are developing the tools to ascertain subtler effects of stimuli on organisms within their habitat; increasingly, organisms are evaluated in terms of environmental and community relationships rather than individual collections of tissues, organs and nerves with a set of adaptive behaviors. Newer behavioral models, along with the increasing accuracy of monitoring technologies will enable us to observe in-habitat animal relationships that include elements of community density and distribution trends, trends in shifting predator/prey relationships, and epidemiology. These meta-themes will give us clues into the impact of anthropogenic noise on the marine acoustic environment.

7.1 Anthropogenic Noise Mitigation

While technology is considered a driving force behind marine habitat destruction, developing technologies will also provide us with opportunities to adapt our harvest and resource extraction operations more efficiently and with more finesse. If we include the importance of ocean quietude into our design criteria, acoustic transducer systems can be designed around more sensitive receivers rather than more powerful transmitters. Digital communication technologies and system-tuned code/decode algorhythms may allow higher data densities without higher acoustic volume. Even seismic exploration can be tailored toward "smaller and more sensitive" rather than "larger and more powerful." Ocean transport noise can be reduced with anti-fouling technologies for hulls and drive systems; low or non-cavitating vortical drives[64] will replace high cavitation 'brute force' propulsion systems. Understanding more about the noise fields generated by various organisms may help fishing vessels locate fish schools with passive SONAR technologies, just as the SOSUS surveillance system allows the U.S. Navy to passively located and identify vessels and submarines. The acoustic illumination method highlighted in this report could be developed for underwater imaging using only ambient noise.[65]

The Navy could continue development of SOSUS accuracy for vessel surveillance, and perhaps use remotely operated reconnaissance vessels for submarine communication and surveillance purposes. In this setting, the use of current SURTASS/LFAS technologies would be a strategic (and environmental) liability; a quieter sea would more clearly reveal the position of loud signal sources generated by active SONAR technologies.

Research funding in any field is directly proportional to economic benefit. Only as biologists are sounding alarms of mass extinction are studies being sponsored that focus on habitat preservation and long-term viability of our planetary biosphere. The survival of our species is dependent on the viability of the ocean fisheries. As we become more acquainted with the dependence of these fisheries on sound, we can focus our research and tailor our activities to promote a quieter marine acoustic environment.

Appendix

A.1.0 Sound behavior in the ocean

One of the most distinct differences between airborne sound and underwater sound lies in the density of each medium. Water is 3500 times denser than air, so sound travels five times faster in water than in air. Density also accounts for the ability of water to transmit sound energy over long distances better than air. The deep ocean also acts as an expansive open space; there are no trees, roads, grassy fields and houses to block and attenuate noises created within the expanse. These factors account for how sound can travel great distances underwater.

Sound is an oscillation over time that is generated by some mechanical action at a location. The energy imparted by the mechanical action moves away from the source at a particular velocity and causes two types of actions; it causes an oscillation in pressure in the surrounding environment, and it causes an oscillating movement of particles in the medium. These properties are true for sound in air as well as in water.

A.1.1 Soundwaves and Ocean Geometry

One of the characteristics of the oscillation of pressure is "wavelength" – a pressure gradient over a distance. Sound wavelengths in water or air can be measured much in the same manner that waves at the beach can be measured – it terms of the distance from crest to crest. This wavelength is dependant on the frequency. The energy of these waves moves at a predictable speed in the medium, so if the frequency of the waves increases, the distance between them gets shorter. If the arrival time increases (the frequency is lowered) the distance between the crests, or wavelength, gets longer.

The relationship between wavelength and frequency is also dependent on how fast sound moves in the medium. In air sound moves at approximately 1000 feet per second. In water sound moves at approximately 5000' per second. This means that the wavelength for a given frequency in water is five times its wavelength in air.

Sound energy moves faster in water because water is denser than air. From this we can surmise that the speed of sound is dependent on density. Sound moves faster in denser mediums (in water sound energy travels at ~ 5000 ft./sec., in steel it travels at ~16,000 ft./sec.). This is important particularly in water because there are three factors that influence the density of water: temperature, pressure and salinity. In the deep ocean – away from rivers and estuaries – salinity is relatively constant. The pressure gradient is also constant in that the pressure increases in direct proportion to depth – approximately one 'atmosphere'[66] for every 34 feet in depth.

Near the surface of the sea, wave action and solar heating cause turbulence that is weather dependant. This surface zone also exhibits seasonal and diurnal changes in temperature that affect the transmission of sound. Below this zone there is a thermal boundary that defines an "isotherm" or deep layer where the ocean temperature is relatively stable at ~4º C. The depth of this boundary varies from near the surface to

4,000 feet, depending on season and proximity to the arctic latitudes. (See chart 1.1.1a in appendix from Urick p. 118.) This abrupt thermal and density boundary acts as a sound reflective surface underwater. Sound generated above the isotherm will tend to bounce off of it back up toward the surface; sound generated below it will bounce down back into the deep.[67] This characteristic creates a 'channeling' effect, whereby sound generated within a layer will tend to remain in the layer, channeling over the curvature of the earth adhering to the layer it is generated in. (See chart 1.1.1b in appendix from Urick p. 160.) In the surface layer, sound will diffract off of the surface irregularities and diffuse through surface turbulence. This is particularly the case with shorter wavelength, higher frequency sound, where the shorter wavelengths interact with surface conditions. As a result, the channeling affect at the surface is better at lower frequencies than at higher frequencies – but in any case, subject to the vagaries of weather and turbulence.

In the isotherm, the channeling is considerably more pronounced as sound is not scattered by turbulence, and the depth is not a limiting factor on wavelength.[68] In this "sound channel," whales have been heard at distances exceeding 1500 miles, and anthropogenic noise has been transmitted over 11,000 miles in the Heard Island Feasibility Test (HIFT).[59]

Due to the long-range characteristic of sound channel transmission, it is likely that whales that produce loud sounds use it for long-distance communication. It is also likely that migrating animals also use the sound channel's acoustical cues for navigation – deriving location cues by listening to the distance and sources of waves and currents interacting with ocean geography.[7]

A.1.2 Particle Motion

The second type of action imparted on the environment by acoustical energy is termed particle motion. This term is not specific to the movement of actual particles suspended in the water, but rather it is a description of the subtle movement of the water molecules back and forth, compressing and relaxing the medium along the axis of sound transmission. Their distance of travel in water is typically miniscule, and animal's organs sensitive to this type of motion are also used to sense turbulence or the close-by movement of prey or predator[69].

Acknowledgements

The author would like to thank Mark J. Palmer with Earth Island Institute for his participation on this report, and Earth Island Institute for sponsoring it. He would also like to thank John Potter with the Acoustic Research Laboratory, Crescent, Singapore for engaging in correspondence about acoustic imaging. Deep gratitude to William Wilgus, who voluntarily combed though this manuscript with a thorough editor's hand. Additional thanks are due to the many dedicated environmental advocates who continue to work for the acoustical sanctity of the sea.

References

Abbreviations:

JASA – Journal of the Acoustical Society of America
JEB – Journal of Experimental Biology

[1] Donald P. Love and Don Proudfoot "Underwater Noise Due to Marine Life" JASA Vol. 18 #2 Oct. 1946
[2] Mark Schrope "Whale deaths caused by US Navy's sonar" Nature # 415, Vol. 106. Jan 10, 2002
[3] Potter J.R., Delory E "Noise sources in the sea and the impact for those who live there" Acoustics and Vibration Asia '98, Singapore, Nov.1998
[4] Decibel (dB) references in this document are expressed relative to 1μPascal per convention when referring to sound underwater. Decibels in an airborne environment are most commonly referred to relative to 20μPascals – the apparent threshold of human hearing. The numerical difference between these two references expressed in decibels is 26dB. For this reason, citations to underwater noise an sound sources may seem quite high for those most familiar with airborne sound level expressions. For a more thorough explanation of the numerical differences between underwater and airborne sound see M. Stocker "How Loud is the Navy Noise?" Earth Island, 2002
[5] R.J. Urick "Principals of Underwater Sound" Ch. 7 "The noise background of the sea." Peninsula Publishing, Los Altos, CA 1983
[6] I. Dyer "The Song of Sea Ice and other Arctic Ocean Melodies" 1984 in "Arctic Technology and Policy" ed. I Dyer and C. Chryssostomidis. McGraw Hill
[7] Clark, C.W. "Blue deep voices: Insights from the Navy's Whales '93 program." Whalewatcher vol.28 (1):6-11. 1994.
[8] Hubert and Mable Frings "Animal Communication" 1977 Univ. of Oklahoma Press
[9] R.J. Urick, 1983 (ref. [5])
[10] S.S. Stevens, Fred Warshofsky "The Evolution of the Ear" 1965 in "Sound and Hearing" Time-Life Science Library.
[11] Potter J.R. & Chitre, M.A. "Ambient noise imaging in warm shallow seas; second-order moment & model-based imaging algorithms" JASA 106(6) 1999
[12] Peter H. Rogers "What are fish listening to?" JASA Suppl. 1, Vol. 79 1986
[13] J. Engelmann, W. Hanke, J. Mogdans & H. Bleckmann "Neurobiology: Hydrodynamic stimuli and the fish lateral line" 2000 Nature 408, 51 - 52
[14] Tavolga, W.N., Wodinski, J. "Auditory Capacities in fishes. Pure tone thresholds in nine species of marine teleost." Bulletin of the American Museum of Natural History. V.126 177-240 p 133-145
[15] Otis, L.S., Cherf, J.A., Thomas, G.J. "Conditioned inhibition of respiratory and heat rate in goldfish."
[16] Due to the speed of sound in water, lower frequency, longer wavelength sounds require either large tanks or pressure coupled apparatus to test. The former is often not available due to real-estate constraints, the latter does not accurately reflect true habitat conditions. Testing tanks that are constructed with parallel sides and bottom are also subject to specular reflections that would influence frequency linearity at various frequencies.
[17] With apologies to Ludwig Wittgenstein.
[18] Alwynne Wheeler, J.W. Jones "Fishes" The New Larousse Encyclopedia of Animal Life 1981 p. 258
[19] Edwin R. Lewis, Ellen L. Leverenz, William S. Bialek "The Vertebrate Inner Ear" CRC Press 1985
[20] Ibid. p. 27
[21] A.D. Hawkins. "The Hearing Abilities of Fish" Chapter 6 in "Hearing and sound communication in fishes" 1981 ed. by William N. Tavolga, Arthur N. Popper, Richard R. Fay. Springer-Verlag.
[22] Chapman, C.J., Sand, O. "Field studies of hearing in two specimens of flatfish *Pleuronectes platessa* (L.) and *Limanda limanda* (L.)" 1974 Journal of Comparative Biochemistry and Physiology V.47A p.371-385 Provided a prosthetic "hearing aid" to a flounder and determined that its hearing would improve 10dB with a swim bladder.
[23] Wever, E.G. "The evolution of vertebrate hearing" in "Handbook of Sensory Physiology" Vol. 1, 1974 Keidel, W.D. and Neff, W.D. eds. p. 423
[24] Olav Sand "The lateral line and sound reception" Chapter 23 in "Hearing and sound communication in fishes" 1981 ed. by William N. Tavolga, Arthur N. Popper, Richard R. Fay. Springer-Verlag.

[25] J. Engelmann, W. Hanke, J. Mogdans & H. Bleckmann "Neurobiology: Hydrodynamic stimuli and the fish lateral line" Nature 408, 51 - 52

[26] Olav Sand, 1981 (ref. [23])

[27] W.N. Tavolga "Mechanisms for directional hearing in the sea catfish (Arius felis)" 1977 JEB Vol. 67, Issue 1 97-115

[28] B.L. Partridge, T.J. Pitcher "The sensory basis of fish schools: relative roles of lateral line and vision." Journal of Comparative Physiology, 1980 vol. 135 p. 315-325

[29] P.H. Cahn "Sensory factors in the side-to-side spacing of Tuna, *Euthynnus affinis"* 1970 U.S. Fisheries Bulletin vol. 70(1) p.197-204

[30] R.D. McCauley, J. Fewtrell, A.J. Duncan et. al. "Marine Seismic Surveys: Analysis and Propagation of Air Gun Signals and Effects on Humpback Whales, Sea Turtles, Fishes and Squid." 2000, Curtin University of Tech., Center For Marine Science and Technology Publication.

[31] Andrew H. Bass "Listening in the dark: Behavioral and neural mechanisms of acoustic recognition in singing fish" JASA 2001 Paper delivered to the 142nd meeting.

[32] Arthur A. Myrberg Jr. "Underwater Sound – Its effects on the Behavior of Sharks" in "Sensory Biology of Sharks, Skates and Rays" 1978 Edward S. Hodgson, Robert R. Matherson eds. ONR:

[33] Arthur A. Myrberg, Jr., Charles R. Gordon, and A. Peter Klimley "Rapid withdrawal from a sound source by open-ocean sharks" JASA 1978 Volume 64, Issue 5

[34] Arthur N. Popper, Xiaohong Deng, John Ramcharitar, and Dennis M. Higgs "The enigma of fish ear diversity." Paper delivered to the December 2000 Acoustical Society meeting

[35] Hubbard, S.J. "Hearing and the Octopus Statocysts" 1960 JEB v. 37

[36] R.D. McCauley, J. Fewtrell, A.J. Duncan et. al. 2000. p 185 (ref. [25])

[37] Ibid. p 185

[38] Dimitri M. Donskoy, Michael Ludyanskiy, David A. Wright, "Effects of sound and ultrasound on Zebra Mussels" JASA April 1996 -- Volume 99, Issue 4. Paper delivered to ASA meeting.

[39] H. Frings "Problems and Prospects in Research on Marine Invertebrate Sound Production and Reception" 1964 in "Marine Bio-Acoustics" William N. Tavolga ed.

[40] Laurence H. Field and Thomas Matheson "Chorodotonal Organs of Insects" Advances in Insect Physiology 27. 1 - 228

[41] Salmon, M, K Horch & GW Hyatt (1977) "Barth's myochordotonal organ as a receptor for auditory and vibrational stimuli in fiddler crabs *Uca pugilator and U. minax*." Marine Behav. Physiol. 4:187-194

[42] Michael Klages and Sergey I. Muyakshin, "Mechanoreception for food fall detection in deep sea scavengers" JASA 1999 Vol. 105, Issue 2

[43] John R. Potter and Teong Beng Koay, "Do snapping shrimp chorus in time or cluster in space? Temporal-spatial studies of high-frequency ambient noise in Singapore waters" Proceedings of the Fifth European Conference on Underwater Acoustics, ECUA 2000 Edited by P. Chevret and M.E. Zakharia, Lyon, France, 2000

[44] Lindberg, R.G. 1955 "Growth, populations dynamics and field behavior in the spiny lobster *Palinurus interruptus* (Randall) Univ. Calif. Publication in Zoology. V. 59

[45] Hubert and Mable Frings "Animal Communication" 1977 Univ. of Oklahoma Press

[46] Salmon, M. and J.F. Stout "Sexual discrimination and sound production in *Uca pugilator*" 1962 Zoologica V. 47 15 - 20

[47] S.S. Stevens, Fred Warshofsky "The Evolution of the Ear" 1965 in "Sound and Hearing" Time-Life Science Library.

[48] Pumfrey, R.L. "Hearing" 1950 in "Physiological Mechanisms in Animal Behavior" 1950 Symposium of the Society of Experimental Biology, Vol. IV Academic Press, N.Y.

[49] Frings, H. and M. Frings. "Underwater sound fields and behavior of marine invertebrates." 1967 Marine Bio-Acoustics. Tavolga W.N. ed. Oxford, UK Pergammon Press.

[50] I'm not naming names here, but this study used glass pipettes to stimulate sea anemones with water pressure. In this paper, the researcher indicated that they could insert the pipette into the mouth of the anemone and inflate it until it burst. The comment on this observation was that the creature did not show subtle response to being killed thus, so it probably needed robust stimulus to induce response.

[51] "IUSS/ISR Program History" 2000 U.S. Navy website http://c4iweb.spawar.navy.mil/pd18/pd18hist.htm

[52] Anonymous, “Using Cold-War Technology to Study Distribution and Behavior of Large Whales Research Utilizing the Integrated Undersea Surveillance System (IUSS)” 1998. from the Whale Research Program at the Cornell Lab of Ornithology

[53] R.J. Urick “Principals of Underwater Sound” Ch. 7 “The noise background of the sea.” Peninsula Publishing, Los Altos, CA 1983

[54] Lloyd's Register of Shipping "World Fleet Statistics"

[55] Kenneth Chang, “Researchers Study Beluga Whales' Responses to Shipping Noise in Canadian Rivers” quoting Peter Scheifele, researcher, National Undersea Research Center at the University of Connecticut in St. Lawrence Seaway peak noise levels.

[56] From Faruno company data sheets for commercial and industrial depth sounders and fish finders.

[57] From Benthos company datasheets for industrial transponders, positioning and locating devices.

[58] Department of the Navy “Final Environmental Impact Statement for SURTASS/LFA Sonar” 2001

[59] R.Reeves, R. Hofman,G.Silber, D.Wilkinsen “Acoustic Deterrence of Harmful Marine Mammal-Fishery Interactions” 1996 workshop proceedings. NOAA, NMFS

[60] George Iwama, Linda Nichol and John Ford “Aquatic Mammals and Other Species: Discussion Paper” 1998 Salmon Aquaculture Review.

[61] Arill Engås, Svein Løkkeborg, Egil Ona, and Aud Vold Soldal “Effects of seismic shooting on local abundance and catch rates of cod and haddock” 1996 Canadian J. of Fishing and Aquatic Science vol.53

[62] From Benthos company datasheets for industrial transponders, positioning and locating devices.

[63] Victoria Kaharl “Sounding out the ocean’s secrets” 1999 for the National Academy of Science “Beyond Discovery” program.

[64] Australian Maritime College “Open Water Testing for PAX Fluid Systems” 2001 performance report from a low cavitation propeller in the Tom Fink Cavitation Tunnel. Non published.

[65] C.L. Epifanio, J.R. Potter, G.B. Deane, M.L. Readhead and M.J. Buckingham “Imaging in the ocean with ambient noise: the ORB experiments” 1999 JASA 106(6)

[66] An atmosphere is approximately 14.7 lbs./in.^{2}

[67] See the `Critical Angle’ of Snell’s Law, wherein the refraction of sound in a layered medium is described in terms of the transmission velocity in each discrete layer. The dimension of a layer is a limiting factor on the transmission wavelength of the sound in that layer. If the wavelength of the sound at the intersection angle is greater than the thickness of the layer, the sound will reflect back into the layer. Due to the typical dimensions of ocean thermal layers, lower frequencies will tend to remain in the deep – and thicker – isotherm layer creating the ‘sound channel’ effect.

[68] For a more thorough treatment of underwater sound transmission see R.J. Urick “Principals of Underwater Sound” Peninsula Publishing, Los Altos, CA 1983

[69] Peter H. Rogers, Thomas N. Lewis and Michael D. Gray “Startle reflex in fish” JASA Nov. 1995 Volume 98, Issue 5

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Michael Stocker is an acoustician, naturalist, technologist and founding director of Ocean Conservation Research. His forthcoming book “Hear Where We Are: Sound perception and sense of place” (University of California Press) explores how sound affects our sense of placement and how humans and other animals use sound to connect with their surroundings.

