

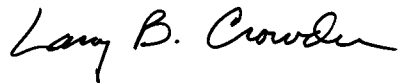
MARINE MAMMALS AND THE EFFECTS OF NOISE:
FACTS ABOUT ACOUSTIC SIGNALS AND
THE POTENTIAL IMPACTS OF
HUMAN SOUND SOURCES

BY

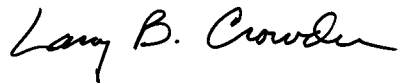
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ABSTRACT

Both natural and human-generated sounds fill the marine environment. Biological processes generate natural sound such as wind, rain, and waves. Humans intentionally produce sound when using sonar or conducting seismic surveys as tools to visualize the underwater world. They produce sound unintentionally through oil and gas exploration and extraction, ocean experiments, and shipping. As sound increases in the ocean, scientists and the general public become increasingly concerned about the potential impact of sound on marine mammals. With these concerns in mind, I undertook a project to provide public outreach and education by producing a brochure for National Oceanic and Atmospheric Administration (NOAA), The American Zoo and Aquarium Association (AZA), Consortium for Oceanographic Research and Education (CORE), and the Marine Mammal Commission (MMC) to distribute during their series of public lectures around the United States to increase public knowledge about human-generated noise and marine animals.

TABLE OF CONTENTS

1 INTRODUCTION.....	1
2 HOW MARINE MAMMALS USE SOUND.....	3
2.1 ECHOLOCATION.....	4
2.2 NAVIGATION.....	6
2.3 COMMUNICATION.....	6
2.4 PREDATOR AVOIDANCE.....	9
3 HUMAN ECOLOGY.....	9
4 OIL AND GAS EXPLORATION, EXTRACTION, AND PRODUCTION.....	11
4.1 SEISMIC SURVEYS.....	12
4.2 INDUSTRIAL NOISE ASSOCIATED WITH OIL AND GAS EXPLORATION, EXTRACTION, AND PRODUCTION.....	13
5 SHIPPING.....	14
6 THE NAVY’S SONAR SYSTEMS.....	16
7 IMPACTS OF HUMAN GENERATED NOISE ON MARINE MAMMALS.....	18
7.1 BEHAVIORAL EFFECTS.....	20
7.2 PERCEPTUAL EFFECTS.....	22
7.2.1 MASKING.....	22

7.2.2 HABITUATION.....	22
7.3 PHYSICAL EFFECTS.....	23
7.4 SPATIAL ZONES OF NOISE INFLUENCE.....	24
8 CONCLUSION.....	26
APPENDIX ONE	
BROCHURE 1: FOR THE SCIENTIFIC COMMUNITY	
APPENDIX TWO	
BROCHURE 2: FOR THE GENERAL PUBLIC	

1 INTRODUCTION

Both natural and human-generated sounds fill the marine environment. Physical or biological processes generate natural sounds such as wind, waves, rain, lightning, cracking ice, volcanoes, earthquakes, and marine mammal noise. Humans also introduce sound into the ocean. Since the dawn of the industrial age, sounds made by human beings have combined with natural ocean sounds, resulting in elevated noise levels. Humans intentionally produce sound when using sonar or conducting seismic surveys as tools to visualize the underwater world. They produce sound unintentionally through oil and gas exploration and extraction; ocean experiments; shipping; and coastal construction and development. Increased uses of the ocean for these activities have led to a higher level of noise pollution over the past few decades. John Hildebrand (2004) estimated that noise levels are at least ten times higher today than they were a few decades ago. As sound increases in the ocean, scientists and the general public become increasingly concerned about the potential impact of sound on marine mammals.

Many factors have combined to escalate interest and concern about the effects of noise on marine mammals. Multi-species strandings took place off the coasts of the Canary Islands in 1985 and 2002, Greece in 1996, Bahamas in 2000, and North Carolina in 2005. All of these incidents coincided with military active sonar operations. For example, in September 2002 when 15 Cuvier's beaked whales simultaneously beached themselves on the Canary Islands, a Navy ship was maneuvering and using high-frequency sonar in the area. After each incident, scientists wondered whether human-generated sounds interfered with the normal use of sound by the marine mammals or whether the human-generated sounds caused the mammals physical harm. Clearly, few

details are known about the characteristics of ocean noise; much less is understood about the impact of that noise on marine mammals and their ecosystem. This issue of marine noise stands out as one of the most sensitive and controversial, yet least understood subjects currently being studied.

Results from a national survey on communicating about oceans show that Americans lack awareness of (1) the importance of the ocean to their daily lives, and (2) its connection to the nation's well being¹. However, most Americans do realize that human behavior can harm the marine ecosystem; they are less knowledgeable about the role individuals play in contributing to this damage². This lack of public understanding about the significance of the ocean hinders efforts to: increase public involvement in ocean-related decision making; achieve responsible use of our ocean; and support management activities³. This lack of knowledge points to the urgent need for education about the oceans. Understanding human impacts on and in the ocean will stimulate recognition of the benefits from well-managed ocean resources⁴.

The Marine Mammal Commission and a number of its partners from the scientific and aquaria community, give public lectures around the United States to increase public knowledge about human noise and marine mammals. However, these agencies do not have educational material to provide to the attendees. So, I teamed up with them to provide public outreach and education materials by producing brochures that they can distribute during the lectures. The agencies involved are the following: the National Oceanic and Atmospheric Administration (NOAA); The American Zoo and Aquarium

¹ Preliminary Report of the U.S. Commission on Ocean Policy, 85.

² Ibid. , 104.

³ Ibid. , 104.

⁴ Ibid. , 86.

Association (AZA); Consortium for Oceanographic Research and Education (CORE); and the Marine Mammal Commission (MMC). These agencies will distribute these brochures during their public lectures series. I produced two brochures. One brochure appeals mainly to the scientific community (see Appendix 1), and the other is geared to the general public (see Appendix 2). The purpose for the lecture series is to increase public knowledge about human-generated noise and marine animals, to present current scientific knowledge about human-generated noise in marine environments, and to identify the effects of human noise. The educational lecture series is entitled “Marine Animals and Human Noise.” The lectures are intended to promote useful discussions among concerned parties, in the hope that involved communities will base future conservation decisions on the best available science. Each lecture is open to the public and to the media, featuring local speakers from academia and government organizations, who will speak at aquariums and research facilities.

This paper goes along with the two brochures to provide a more in-depth analysis on the topics covered in the brochures. I present a comprehensive look at the issues between human-generated noise and marine mammals by covering topics such as: how marine mammals use sound, how the major constituents (oil, gas, and the shipping industry, and the U.S. Navy,) interact with and possibly affect marine mammals, and the possible impacts of human-generated noise on marine mammals.

2 HOW MARINE MAMMALS USE SOUND

The ocean is a dark and noisy place. Marine mammals rely on sound much as people rely on sight to carry out their primary life functions. They use sound to sense and

interact with their environment and to communicate with each other⁵. Many marine mammals use sound to echolocate, navigate, communicate to maintain mother and calf cohesion and group cohesion, to avoid predators, and to announce territorial or reproductive status⁶. Sound clearly plays an important role in the lives of marine mammals.

2.1 ECHOLOCATION

Odontocetes have overcome the problem of orienting themselves and locating objects in the dark (or where vision is otherwise limited) by producing short-duration sounds and listening for reflected echoes as the sounds bounce off objects⁷. Essentially, echolocation is a specialized type of acoustic communication in which an animal sends information to itself.

Echolocation begins with mid to high-frequency sounds (clicks) that originate in a narrow beam in front of an animal's head; it then detects the echoes of those sounds as they bounce off distant objects in order to determine the physical features of their surroundings⁸. Odontocetes are the only cetaceans that can produce echolocation clicks, which they rely on for detecting prey.

Echolocating odontocetes produce forward-projecting pulsed sounds of high intensity and frequency in a narrow beam in the front of their heads. Each pulse is very brief, typically 50-200 μ s in duration⁹.

⁵ National Research Council, *Low-Frequency Sound and Marine Mammals* (Washington D.C.: National Academy Press, 1994), 2.

⁶ W. John Richardson et al. *Marine Mammals and Noise* (San Diego: Academic Press, 1995), 159.

⁷ Annalisa Berta and James L. Sumich, *Marine Mammals: Evolutionary Biology* (San Diego: Academic Press, 1999), 261-271.

⁸ Berta and Sumich, *Marine Mammals: Evolutionary Biology*, 261-283.

⁹ Richardson et al., *Marine Mammals and Noise*, 181-189.

The best-studied echolocation system in marine mammals is that of the bottlenose dolphin. Bottlenose dolphins produce clicks that can have very high peak-to-peak sound pressure levels (up to >220dB re 1 μ Pa at 1 m), but over very short periods (several microseconds), with a total click duration of only 50-80 μ s¹⁰. The clicks often have a relatively broad bandwidth (30-40 kHz) composed of a wide range of frequencies often exceeding 150 kHz, with most of the acoustic energy between 30 and 150 kHz¹¹. As each click strikes a target, a portion of its sound energy is reflected back to the dolphin. The brain of bottlenose dolphins is capable of very rapid auditory processing—their ears integrate high-frequency energy over an interval of about 0.25 ms¹². This specialized hearing is an adaptation for receiving echolocation clicks.

A bottlenose dolphin echolocates by producing a click and then waiting to detect the returning echo¹³. Thus, if a dolphin does not detect an obstacle or a target nearby, it will usually produce clicks with a slow repetition rate. As it closes in on a target, the dolphin will often produce a train of clicks with an accelerating tempo and a decreasing interclick interval.

Beluga whales emit series of clicks with interclick intervals less than the round trip travel time to the sonar target¹⁴. Beluga whales do not have to process each pulse independently, waiting for the echo to return before emitting the next pulse, but rather appear to use a different kind of sonar processing in which they can process whole series of pulses together. Variability in the echolocation signals and hearing specializations of

¹⁰ Hoelzel, *Marine Mammal Biology: An Evolutionary Approach*, 155-159.

¹¹ Ibid. Berta and Sumich, *Marine Mammals: Evolutionary Biology*, 261-283.

¹² Hoelzel, *Marine Mammal Biology: An Evolutionary Approach*, 155-159.

¹³ Ibid.

¹⁴ Ibid.

odontocetes suggests caution in assuming that all species process sonar sounds the same way as bottlenose dolphins do.

An Odontocete unable to produce or hear echolocation clicks would effectively become blind.

2.2 NAVIGATION

The ability to undertake large-scale movements and particularly to return to specific locations, indicates that marine mammals have sophisticated means of navigation. Marine mammals use sight, echolocation, and hearing to detect physical features such as the nature of the seabed, coastline, or ice cover, thus providing general and specific information about their location¹⁵.

Mysticete whales use low-frequency calls to orient themselves to their surroundings and to navigate through the ocean¹⁶. This form of navigation assists the whales on their long, often convoluted migrations to and from breeding and feeding grounds. For example, Bowhead whales use low-frequency calls to monitor the location of the ice edge during spring migration around northern Alaska¹⁷. Unfortunately, many forms of anthropogenic sounds are also produced at these low-frequencies that could interrupt their navigational abilities.

2.3 COMMUNICATION

Communication is a process in which a sender transmits information by sending a signal to a receiver. Communication succeeds when the following are met: a sender

¹⁵ Rus Hoelzel, *Marine Mammal Biology: An Evolutionary Approach* (United Kingdom: Blackwell Publishing, 2002), 205.

¹⁶ Richardson et al., *Marine Mammals and Noise*, 159.

¹⁷ Chris Parsons and Sarah Dolman, "The Use of Sound by Cetaceans," *Oceans of Noise: A Whale and Dolphin Conservation Society Science Report*," accessed from the internet, 44-45

emits a sound or a communication signal; this signal is transmitted to a receiver; it imparts information to the receiver¹⁸.

On land, male pinnipeds competing for females and territory use airborne calls and visual displays during courtship and aggressive encounters. For instance, California sea lions, when underwater, commonly produce bark sounds in aggressive situations¹⁹.

Female pinnipeds and their pups vocalize in air and underwater to maintain contact²⁰.

Pinnipeds and cetaceans that mate in the water use underwater calls to coordinate mating²¹.

Cetaceans communicate within and between species, and due to their marine environment, the majority of this communication occurs in the form of acoustic signals.

Social interactions include mating, sexual activity, play, dominance interactions, and maternal behavior. When in groups, many species of cetaceans are extremely vocal, especially when interacting. Odontocetes use echoes from the high-frequency sound pulses they produce to detect and locate prey, and characterize underwater objects including obstacles²². Individuals use lower-frequency sounds for communication.

Communication is important in maintaining mother and calf cohesion as well as group cohesion.

The cohesion between a mother and her calf is one of the most important social bonds in cetaceans. A calf may stay with its mother for a decade and even longer in some species, cementing their bond through communication. In this way, the calf learns

¹⁸ Andy Read, "Communication," lecture presented to the Marine Mammal class at the Duke Marine Laboratory, October 6, 2004.

¹⁹ Richardson et al., *Marine Mammals and Noise*, 198.

²⁰ Ibid. 159.

²¹ Ibid.

²² Ibid. 160-164.

important life skills, such as how to capture prey. Southern right whale mother-calf pairs use an “up” sound to become rejoined when they become separated beyond underwater visual range (75m)²³. Human-generated sound can disrupt this communication, and may lead to severe debilitation and even death of the dependent calf²⁴.

Cetaceans frequently form foraging groups. Depending on the species, they often travel and feed in groups of three to thousands²⁵. Group foraging allows cetaceans to catch larger and greater quantities of prey, but in order to perform effectively, they need to communicate effectively. Resident killer whales in the Pacific Northwest exemplify this type of behavior. These whales specialize in forming groups to forage for salmon. Each group possesses a distinct call believed to be important in maintaining group cohesion. Lacking this form of communication, the group could possibly break down, and the killer whales would be less successful at catching prey²⁶.

Humpback whales produce different communication sounds depending on the situation. They produce three kinds of sounds: 1) sounds made by solitary individuals, 2) sounds made by whales with groups on the winter grounds, and 3) sounds made while on the summer feeding grounds. Songs sung by solitary males are associated with reproduction and maintaining a distance between other males. This song is presumed to be a reproductive display that allows females to choose the best male possible to father her offspring²⁷. Female humpback whales may assess the fitness of males by their song

²³ Richardson et al., *Marine Mammals and Noise*, 165.

²⁴ Ibid. 46

²⁵ Ibid. 117.

²⁶ Read, “Communication”.

²⁷ Richardson et al., *Marine Mammals and Noise*, 166.

length, which would be an honest indicator of male breath-holding ability²⁸. If females are using male song as a way to choose mates, any changes in song duration or structure could disrupt cetacean courtship behavior.

Humpback whales within groups produce sounds very different from those of solitary animals. Group sounds are often associated with antagonistic behavior among males competing for dominance and proximity to females²⁹.

Humpbacks are less vocal when on feeding grounds. Some researches speculate that this serves for prey manipulation and assembly calls³⁰.

2.4 PREDATOR AVOIDANCE

Because marine mammals are vulnerable to predation by sharks and killer whales, some species produce alarm sounds to provide information on the type of threat so group members can respond appropriately³¹. Human-generated noise that would mask or totally block a distress call, could be a spell death for the mammal at risk.

3 HUMAN ECOLOGY

The relationship between human-generated noise and marine mammals is controversial because marine mammals are considered to be valuable species and the stakeholders involved are of extremely high profile. See figure 1. The biophysical environment encompasses the ocean, air, and land as well as the ocean, air, and land interfaces. Humans generate noise in all three environments. The noises generated on land and in air have potential to transmit into the ocean where they can have an effect on

²⁸ Parsons, "The Use of Sound by Cetaceans", 46.

²⁹ Richardson et al., *Marine Mammals and Noise*, 167.

³⁰ Ibid.

³¹ Parsons, "The Use of Sound by Cetaceans", 46.

marine mammals. The scientific community is made up of scientists that are involved in studying the ocean and marine mammals, such as: marine biologists, oceanographers, acousticians, engineers, biologists, and marine mammal biologists, physiologists, behaviorists, and geneticists. The public policy and management governance arena is split between the Department of Commerce and the Department of Interior. The constituents involved in the relationship between human-generated noise and marine mammals are the following: oil and gas companies, shipping industry, environmental groups, Navies of various countries, dredging and coastal construction companies, researchers and scientists.

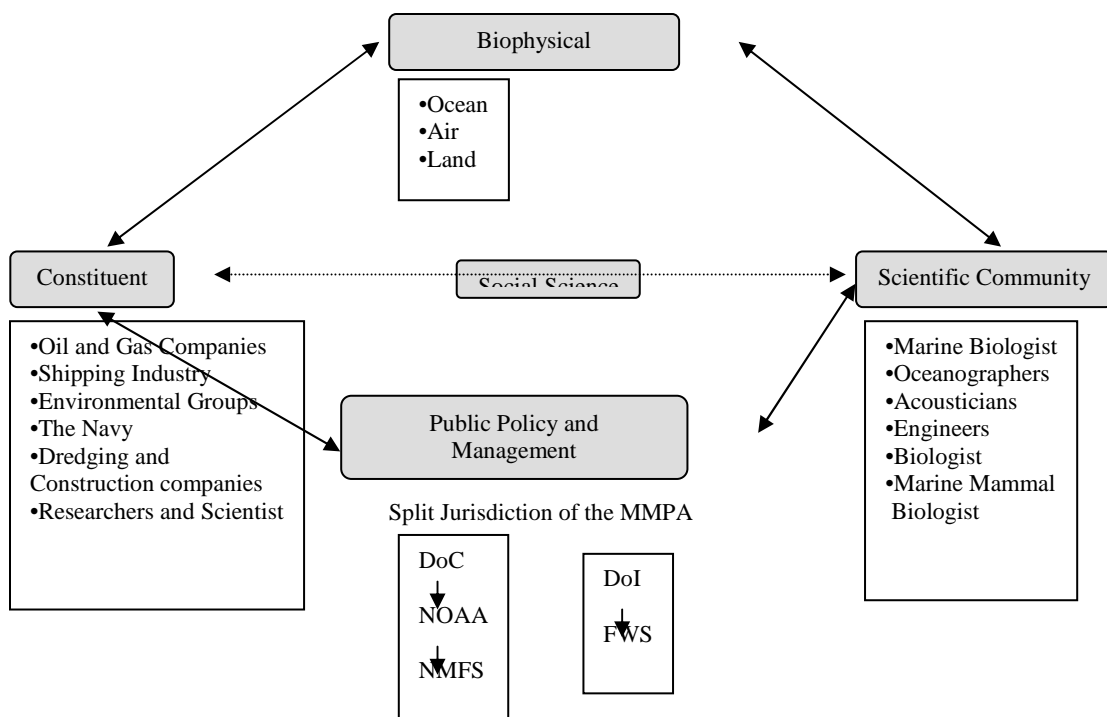


Figure 1. A figure of the human ecology of marine mammals and sound.

The following sections are examples of how the constituents interact with and possibly affect marine mammals.

4 OIL AND GAS EXPLORATION, EXTRACTION, AND PRODUCTION

Offshore oil industry activities occur along the world's coastlines. The major areas of current oil industry activity include northern Alaska and extreme northwest Canada, the east coast of Canada, U.S. Gulf of Mexico, Mexican Gulf of Mexico, offshore Venezuela, offshore Brazil, offshore West Africa, offshore South Africa, North Sea, Middle East, northwest Australia, New Zealand, southern China, Vietnam, Malaysia, and Indonesia³².

The offshore oil industry, which explores the continental shelf, is responsible for a variety of acoustic disturbances. Offshore drilling for oil and gas usually takes place from man-made islands, from platforms, or from drilling ships attended by support vessels³³. Thus, offshore drilling exploration, extraction, and production involve various activities that produce underwater noise.

Oil and gas production is moving into water depths up to 3,000 m. New exploration areas include the deep-water U.S Gulf of Mexico and the deep offshore waters of West Africa, which have both become active in the past 5-10 years. These new deep-water fields may be a source of greater noise than the shallow-water fields have traditionally been, because drilling at depth requires drill ships and floating production, storage, and off-loading systems on a weekly basis. This trend towards oil and gas

³² NRC, 2003, 64.

³³ Richardson et al., *Marine Mammals and Noise*, 127-135.

exploration in deep, offshore waters has increased the potential for conflict with marine mammals that are low-frequency specialists, such as mysticete whales.

4.1 SEISMIC SURVEYS

Offshore seismic surveying, the predominant technique employed by the oil and gas industry, uses intentionally created sound. Other activities such as pipe-laying primarily create unintentional noise. Seismic surveys produce high intensity, low-frequency sounds towards the bottom of the ocean in order to provide information about the structure and composition of geological formations and to identify potential hydrocarbon reservoirs³⁴. The major operational elements of a seismic survey are (1) the seismic vessel; (2) one or two airgun arrays towed about 200 m behind the seismic vessel; and (3) cables containing large numbers of hydrophone sensors towed behind the vessel³⁵.

The airguns discharge tens of thousands of blasts intense enough to ricochet off layers of sedimentary rock on the ocean floor³⁶. This array of airguns emits an acoustic signal by releasing a volume of compressed air into the water column; hydrophones record the reflected sounds waves³⁷. Several pulses are emitted per minute, usually at uniform intervals³⁸. The maximum sound pressure level that a mammal could experience

³⁴ Ibid.

³⁵ NRC, 2003, 58.

³⁶ Michael Jasny, *Sounding the Depths: Supertankers, Sonar, and the Rise of Undersea Noise* (Natural Resources Defense Council, 1999) accessed from the internet www.nrdc.org/wildlife/marine/sound/sdinx.asp.

³⁷ Chris Parsons, Rene Swift and Sarah Dolman, "Sources of Marine Noise," *Oceans of Noise: A Whale and Dolphin Conservation Society Science Report*, accessed from the Internet, 24-44. Richardson et al., *Marine Mammals and Noise*, 127-135.

³⁸ R. E. Harris, G. W. Miller, and W. J. Richardson, "Seal Responses to Airgun Sounds During Summer Seismic Surveys in the Alaskan Beaufort Sea," *Marine Mammal Science* 17(2001): 796.

from an airgun would be in the range of 235-240 dB re 1 μ Pa (RMS)³⁹. Each seismic session can last several hours and the entire survey can take up to several months.

Even though the greatest sound intensity is downward, a significant amount of energy is radiated away from the sound source—the beam axis. These propagation characteristics imply that the sound levels received by a mammal located close to the sound source will depend on its depth and position relative to the array's axis. Those mammals beneath the axis might experience a greater sound pressure than those off to one side or another. Similarly, mammals deeper in the water yet directly below the array might receive a higher intensity sound than those mammals closer to the surface but in the same range from the array⁴⁰. Source levels of pulses from airgun arrays are strong enough to raise concern that such pulses might cause temporary or even permanent hearing damage to marine mammals within range.

4.2 INDUSTRIAL NOISE ASSOCIATED WITH OIL AND GAS EXPLORATION, EXTRACTION, AND PRODUCTION

Many activities associated with oil and gas generate underwater noise. These activities range from pipe-laying to drilling to explosive wellhead decommissioning⁴¹. In general, drill ships are the noisiest type of drilling equipment, with a source pressure level across the 10 Hz to 10 kHz band of about 190 dB re 1 μ Pa at 1 m. Drill ships are expected to be the noisiest because the large hull is an efficient transmitter of all of the ship's internal noises, and the ships do not anchor but instead use thrusters to remain in place, resulting in propeller noise much of the time during the drilling operation⁴².

³⁹ NRC, 2003, 60.

⁴⁰ Parsons, "Sources of Marine Noise", 28.

⁴¹ Ibid. 24-44.

⁴² NRC, 2003, 63.

Ship machinery, propellers, and natural structural vibration also emit noise. Machinery noise is the result of mechanical vibration emitted from a ship hull, from oil platform legs, or through the ground⁴³. Causes of propeller noise are cavitations and propeller-induced vibration⁴⁴. Citing structures offshore creates some localized unintentional noise for brief periods of time.

5 SHIPPING

Ambient noise in the world's oceans rose by as much as 10 decibels, one full order of magnitude, between 1950 and 1975⁴⁵. Shipping is probably to reason; with the advent of the global economy, the merchant fleet has doubled in size, gross tonnage has quadrupled, and the cumulative noise from so much traffic now dominates the lower frequencies in many regions of the world⁴⁶. Commercial shipping, however, is not uniformly distributed. The major lanes are great circle routes or follow coastlines to minimize time at sea. The U.S. Navy's Space and Naval Warfare Systems Command defines 521 ports and 3,762 traffic lanes in its efforts to catalogue commercial and transportation marine traffic⁴⁷.

Vessels ranging from the smallest boats to the largest supertankers all produce underwater sounds, making them major contributors to the background noise in the sea, especially when considering their large numbers, wide distribution, and mobility⁴⁸. The primary sources of sound from vessels are propeller cavitations, propeller singing, propulsion, and other machinery. Propeller cavitations are usually the dominant noise

⁴³ Parsons, "Sources of Marine Noise", 24-44.

⁴⁴ Ibid.

⁴⁵ Parsons, "Sources of Marine Noise", 24-44.

⁴⁶ Jasny, *Sounding the Depths: Supertankers, Sonar, and the Rise of Undersea Noise*, 2.

⁴⁷ NRC, 2003, 50.

⁴⁸ Richardson et al., *Marine Mammals and Noise*, 110-123.

source. “Propeller singing arises when vortex shedding frequencies reinforce a resonant vibrational frequency of a propeller blade⁴⁹.” Propulsion and machinery noise originate inside the vessel and reach the water via the vessel hull. Sources of sound include rotating shafts, gear reduction transmissions, gear teeth, mechanical friction, pumps, generators, flow noise from water dragging along the hull, and bubbles breaking in the wake. The levels and frequency characteristics are related to ship size and speed⁵⁰.

Large commercial vessels such as oil and gas tankers, general cargo/freighter, and cruise ships generate sound at a low-frequency range, less than 1 kHz⁵¹. Large vessels create stronger and lower-frequency sounds because of their greater power, large drafts, and slower-turning engines and propellers⁵². They also have larger hulls to convey more machinery sound to the water. A low-frequency range of less than 1 kHz coincides with frequencies used by baleen whales for communication and other biologically important activities.

Small commercial vessels such as ferries, fishing boats, inland and coastal tug/barges generate sound at a high-frequency range between 1 kHz to 50 kHz⁵³. These vessels have smaller propellers with higher rotation rates than larger boats resulting in cavitation noise at higher-frequencies⁵⁴. The higher-frequency sound generated from the

⁴⁹ Richardson et al., *Marine Mammals and Noise*, 110-123.

⁵⁰ John Hildebrand, “Sources of Anthropogenic Sound in the Marine Environment” (California: Scripps Institution of Oceanography, University of California San Diego, 2004) access from the Internet at www.mmc.gov.

⁵¹ “Uses and Characteristics of Anthropogenic Sound in the Marine Environment: Shipping Generated Sound”, PowerPoint presentation given at the First Plenary Meeting of the Advisory Committee on Acoustic Impacts of Marine Mammals on 3-5 of February 2004.

⁵² Richardson et al., *Marine Mammals and Noise*, 111.

⁵³ “Uses and Characteristics of Anthropogenic Sound in the Marine Environment: Shipping Generated Sound”, 2004.

⁵⁴ Richardson et al., *Marine Mammals and Noise*, 111.

propellers could be disturbing the smaller cetaceans that would appear to be more sensitive to high-frequency sounds.

Other vessels such as military craft, fishing boats, single vessels, and scientific research ships, occur in widely distributed areas of the oceans outside of ports and shipping lanes. Most of the recreational boating activity takes place in shallow coastal water, environments inhabited by many marine mammal species. The number of boats owned in the United States increased from 15.8 million in 1995 to 17 million in 2001, representing more than a 7% increase⁵⁵.

Trends indicate that the increase in number of vessels is consistent with population growth and use of the sea for economic, recreational, and transportation purposes. Economic pressure for oceanic shipping remains strong. No near-term alternative is available for moving the necessary tonnage of goods and material globally.

6 THE NAVY'S SONAR SYSTEMS

The development of underwater sound as a method for detecting submarines began during World War I and has accelerated rapidly ever since⁵⁶. Sonar systems use acoustic energy to characterize physical properties and locate objects beneath the ocean surface. Two basic types of sonar exist: passive and active. Passive sonar listens passively to sounds within the water. Active sonar emits omni-directional, short pulses of sound designed to focus as much energy as possible in narrow ranges. Active sonar detects objects underwater by sending out a sound pulse that bounces off the target and returns as an echo that the system can detect.

⁵⁵ National Research Council, *Ocean Noise and Marine Mammals* (Washington D.C.: National Academy Press, 2003), 51.

⁵⁶ *Ibid.* 12-26.

The Navy uses sound, in the form of sonar, as an essential tool for ensuring national security. Naval sonar systems can be divided into low-frequency (<1 kHz), mid-frequency (between 1 and 10 kHz), and high-frequency (>10 kHz). The Navy uses low-frequency sonar for surveillance, in order to gather information over large areas such as the entire ocean basin. Mid-frequency systems are tactical sonars designed to look over tens of kilometers for the localization and tracking meant to perform over hundreds of meters to a few kilometers⁵⁷.

Because modern submarines are now much quieter than ever before, enemy vessels can escape detection from passive sonar used on the ocean floor. Therefore, the Navy has decided that long-range, very high-powered, low-frequency active sonar is needed. The U.S. Navy currently uses a form of active sonar known as Surveillance Towed Array Sensor System (SURTASS) Low Frequency Active Sonar (LFA). The SURTASS LFA sonar system meets the Navy's need for improved detection and tracking of new-generation submarines at long range⁵⁸. SURTASS LFA employs very loud low-frequency sounds of less than 500 Hz, with intensity levels as great as 230 dB re 1µPa at 1 m¹⁵, which poses a significant threat to marine mammals⁵⁹. Individual naval ship sonar exercises can last a few hours to a few days; predeployment and battle group exercises normally last 10-12 days; and multinational fleet exercises can last up to a month⁶⁰.

Considerable concern exists about this sonar system and other similar systems such as the United Kingdoms SONAR 2087 because of the loudness of the sources, the

⁵⁷ NRC, 2003, 65.

⁵⁸ "Executive Summary: Final Overseas Environmental Impact Statement and Environmental Impact Statement for Surveillance Towed Array Sensor System Low Frequency Active (SURTASS LFA) Sonar", (prepared for the Department of the Navy, January 2001), ES-2.

⁵⁹ Jon M. Van Dyke, Emily A. Gardner, and Joseph R. Morgan, "Whales, Submarines, and Active Sonar," *Ocean Yearbook 18* (2004): 334.

⁶⁰ NRC, 2003, 66.

distance the sounds can travel (low-frequencies travel farther distances than high frequencies), and tests using these systems have shown short-term and possible long-term behavioral changes in marine mammals in response to the sonar⁶¹.

7 IMPACTS OF HUMAN-GENERATED NOISE ON MARINE

MAMMALS

Over the past decade, scientists have realized that the sounds humans put into the ocean can have significant effects on the behavior and hearing systems of marine animals.

Figure 2 shows the frequency relationships between the sounds marine mammal emit and the noise generated by humans. This figure shows that whales and the noises generated by shipping, seismic surveys, and oil and gas extraction have the same frequency range. Likewise, dolphins and porpoises emit noises in the same frequency range as certain types of sonar. Therefore, dolphins and porpoises are most likely going to be affected by sonar systems, whereas whales, seals, and sea lions will be affected by shipping, seismic survey and oil and gas noises.

⁶¹ Parsons, "Sources of Marine Noise", 24-44.

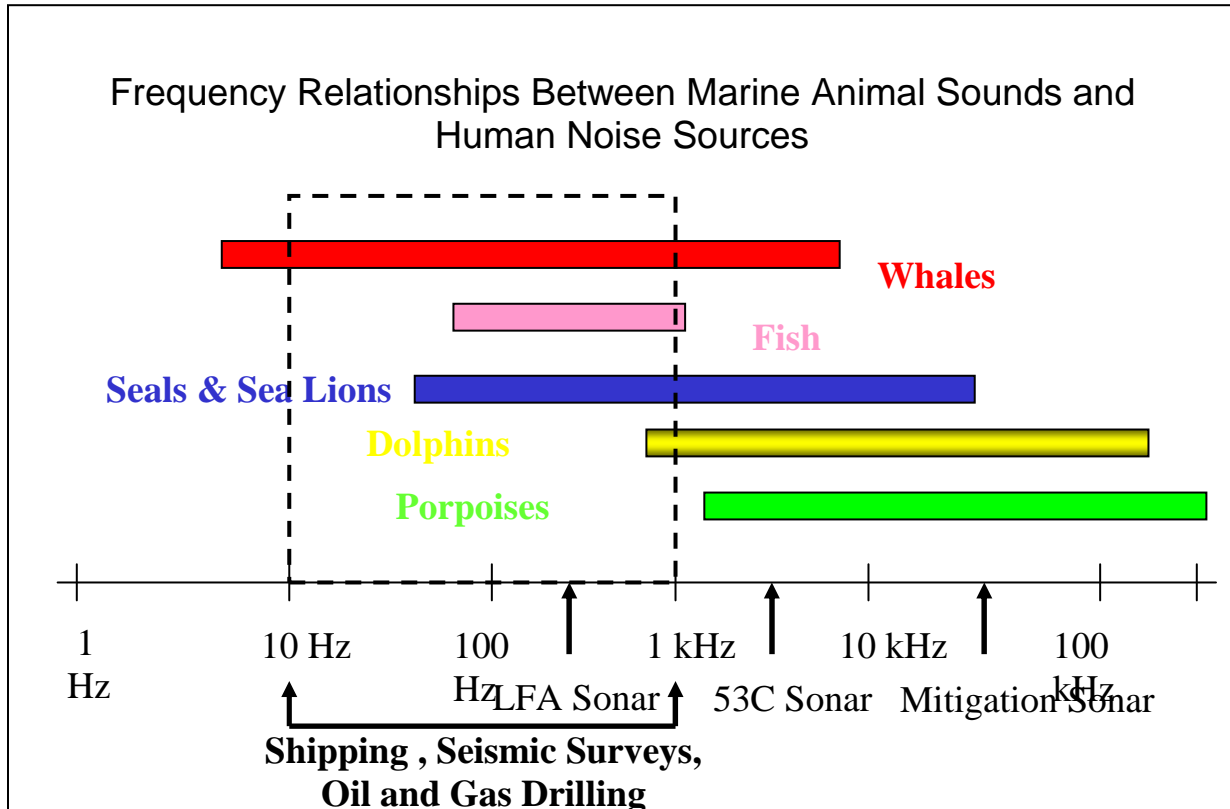


Figure 2: Frequency Relationship Between Marine Animal Sounds and Human Noise Sources. Adapted from Southall (2004)

A number of factors affect the response of marine mammals to sounds in their environment. These responses vary widely, depending on internal and external factors. Internal factors include: individual hearing sensitivity, activity pattern, and motivational and behavioral state at time of exposure; past exposure of the animal to the noise, which may have led to habituation; individual noise tolerance; and demographic factors such as age, sex, and presence of dependent offspring⁶². External factors include: nonacoustic characteristics of the sound source, such as whether it is stationary or moving; environmental factors that influence sound transmission; habitat characteristics, such as

⁶² NRC, 2003, 90.

being in a confined location; and location, such as proximity to a shoreline⁶³. The impacts can range from behavioral to perceptual to physical effects.

7.1 BEHAVIORAL EFFECTS

Human-generated noise may cause short-term behavioral reactions such as cessation of feeding, socializing and vocalizing, changes in diving behavior, displacement of cetaceans from preferred habitats, as well as avoidance of or attraction to the noise source. A common reaction of mammals during exposure to noise is to cease or reduce calling and vocalizing⁶⁴. This change in calling could indicate some social disruption. The same changes in calling behavior have been documented in right whales' response to boats⁶⁵, in sperm whales' response to short sequences of pulses from acoustic pingers⁶⁶, and in bowhead whales' response to playbacks of industrial sounds⁶⁷. Many cetaceans are known to cease vocalizing for hours or even days after encounters with low-frequency noise, and in severe cases, the silence may become chronic, a permanently disabling response⁶⁸.

Approach and/or avoidance of a noise source is considered a disturbance because the noise causes a mammal to alter its natural behavior⁶⁹. Mammals that approach a noise source in order to investigate it may be placing themselves in greater danger.

Aggregated mammals may flee in different directions upon the approach of a fast moving

⁶³ NRC, 2003, 90.

⁶⁴ Richardson et al., *Marine Mammals and Noise*, 395.

⁶⁵ W.A. Watkins, "Whale Reactions to Human Activities in Cape Cod Waters," (*Marine Mammal Science* 2: 251-262, 1986).

⁶⁶ W.A. Watkins and W.E. Schevill, "Sperm Whales (*Physeter catodon*) React to Pingers," (*Deep-Sea Research* 22: 123-129, 1975).

⁶⁷ D. Wartzok, W.A. Watkins, B. Würsig, and C.I. Malme, "Movements and Behaviors of Bowhead Whales in Response to Repeated Exposures to Noises Associated with Industrial Activities in the Beaufort Sea," Report from Purdue University for Amoco Production Company, Anchorage, AK, 1989.

⁶⁸ Jasny, *Sounding the Depths: Supertankers, Sonar, and the Rise of Undersea Noise*, 6.

⁶⁹ Chris Parsons and Sarah Dolman, "Noise as a Problem for Cetaceans," *Oceans of Noise: A Whale and Dolphin Conservation Society Science Report*, accessed from the Internet, 53.

noisy vessel, which may increase aggression while the social order is in flux. Gray whales have been seen avoiding 120-decibel sounds, altering their migration routes by a mile or more to distance themselves from the sound⁷⁰. Obviously, displacement or avoidance of key habitat due to noise could have profound effects; loss of feeding grounds for example might deteriorate these populations, leading to increased morbidity and mortality. Also, social disruption decreases or disrupts natural activities—mating, feeding, nurturing.

Even so, mammals busy with social activities are somewhat less likely to be disturbed by noise than mammals that are resting. Würsig summarized the responses of several species of dolphins to boats as “resting dolphins tend to avoid boats, foraging dolphins ignore them, and socializing dolphins may approach.”⁷¹

Responses of mammals also vary depending on where the mammals are when they encounter a noise source. For example, beluga whales are more sensitive to ship noise when they are confined to open-water leads in the spring ice; migrating gray whales diverted around a stationary sound source projecting playback of LFA sonar when the sound was located in their migratory path, but they seemed to ignore the sound when it was located seaward of the migratory path⁷².

Clearly, there are costs associated with behavioral changes. Every movement a mammal makes requires energy that might have been used for acquiring food or mates or enhancing reproduction. Even where there is no measurable behavioral response, we cannot assume that no biological consequences result from exposure to loud noises.

⁷⁰ Jasny, *Sounding the Depths: Supertankers, Sonar, and the Rise of Undersea Noise*, 6.

⁷¹ Personal observation cited in Richardson et al., *Marine Mammals and Noise*.

⁷² J.J. Burns and G.A. Seaman, “Investigation of Belukha Whales in Coastal Waters of Western and Northern Alaska II—Biology and Ecology,” U.S. National Oceanic and Atmospheric Administration, 129. NRC, 2003. 92.

7.2 PERCEPTUAL EFFECTS

7.2.1 MASKING

At certain frequencies, human generated noise affects marine mammals indirectly, by masking biologically significant sounds, making them undetectable by cetaceans. Masking is the reduction in a mammal's ability to detect relevant sounds in the presence of other sounds⁷³. As previously mentioned, biologically important sounds emitted by mammals include: echolocation clicks for finding prey; sound cues from conspecifics, prey or predators; courtship or group vocalizations; call made for navigational aid; and calls between mothers and calves. The human-generated sounds make it more likely that cetaceans will be unable to feed, that they will be attacked by predators, and that they will be unable to socialize, reproduce or rear their young. Moreover, they may be unable to migrate properly from breeding and feeding grounds. These impacts of masking may be most pronounced in species that rely on long-range communications, such as the blue and fin whale are thought to do⁷⁴.

7.2.2 HABITUATION

Habituation occurs “when the stimulus is no longer novel although adverse consequences may still be associated with it.” Gradual deafness might easily be misinterpreted as a growing tolerance or habituation to noise⁷⁵. Evidence of habituation comes from attempts to use sound to keep mammals away from an area through the use of acoustical harassment devices (AHDs). Cox et al. (2001), found that harbor porpoises habituate to pingers (type of AHD) placed on gillnets in an attempt to reduce the porpoise

⁷³ NRC, 2003, 96.

⁷⁴ Jasny, *Sounding the Depths: Supertankers, Sonar, and the Rise of Undersea Noise*, 6.

⁷⁵ Chris Parsons and Sarah Dolman, “Noise as a Problem for Cetaceans,” 56.

bycatch. Their results showed that the probability of the porpoises being within 125 m of a pinger decreased at first, but within 10-11 days, had increased to equal the control⁷⁶.

7.3 PHYSICAL EFFECTS

Sound is a physical phenomenon: a force passing like a wave through water or air, compacting and refracting the molecules it crosses. Intense noise causes sudden pressure changes resulting in physiological damage in mammals within range of the noise. Ketten divides the physiological effects of intense noise into two categories: (1) lethal blast injuries; and (2) sub-lethal acoustic trauma⁷⁷. Lethal effects are those that result in the immediate mortality or serious debilitation of mammals in or near an intense noise source. Sub-lethal effects occur when sound levels exceed the ear's tolerance. For example, noise-induced trauma is possible from high levels of shipping noise. Sub-lethal impacts can lead indirectly to death in cetaceans as they render animals unable to detect prey or predators; they may also be unable to orient themselves or to avoid shipping lanes or obstacles. Ketten further divides sub-lethal acoustic trauma into three categories. See Table 1.

1	Mild	Pain, Vertigo, Tinnitus, Hearing loss, Tympanic tears	Recovery possible
2	Moderate	Tympanic membrane haematoma, blood in inner ear, dissection of the mucosa	Partial hearing loss
3	Severe	Ossicular fracture or dislocation, CSF leakage into inner ear, cochlear and saccular damage	Permanent hearing loss and damage

Table 1: Three categories of sub-lethal acoustic trauma (from Ketten 1995).

⁷⁶T.M. Cox, A.J. Read, A. Solow, and N. Tregenza, "Will Harbour Porpoises (*Phocoena phocoena*) Habituate to Pingers?" *Journal of Cetacean Research Management* 3: 81-86, 2001.

⁷⁷ D.R. Ketten, "Estimates of Blast Injury and Acoustic Trauma Zones for Marine Mammals from Underwater Explosives," *Sensory Systems of Marine Mammals*: 391-407, 1995.

Prolonged exposure to continual noise, as from shipping and airguns, may cause hearing loss, analogous to the ringing of the ears we experience after a rock concert and friends have to raise their voices to be heard. Audiologists call this impairment “threshold shift”. After, exposure to a damaging noise, one’s acoustic threshold rises, sometimes by a few decibels—thereby increasing deafness. For a marine mammal, each additional decibel can mean the loss of vital information: the call of a calf, or of a predator, or of a prospective mate⁷⁸. Threshold shift can last temporarily or permanently, depending on the duration and intensity of exposure.

7.4 SPATIAL ZONES OF NOISE INFLUENCE

The impact that one of these sources may have on a mammal depends on the distance of the sound source. Being close to the source may cause tissue in the lungs, ears or other parts of the body to rupture. Being farther away from the sound can cause temporary or permanent hearing loss, and can affect the behavior of the mammals. Richardson et al. identified four concentric zones of influence with decreasing size and increasing intensity of the signal. The largest zone is that of audibility, followed by behavioral disturbance, then masking, and finally the zone of hearing loss, discomfort, or injury⁷⁹. See figure 3. The closer they are to the center of the sound source the more damaging the effects can be on marine mammals.

The zone of audibility is the most extensive area within which the mammal might hear the noise. The maximum radius of the zone of audibility of human-generated sound on a marine mammal is the distance from the noise source at which the noise can barely be heard. This distance is determined by the hearing sensitivity of the mammal or the

⁷⁸ Jasny, *Sounding the Depths: Supertankers, Sonar, and the Rise of Undersea Noise*, 6.

⁷⁹ Richardson et al., *Marine Mammals and Noise*, 326-381.

background noise level⁸⁰. Because the radius of this zone depends on the receiving mammals' hearing ability, this radius may vary widely depending on the species and individual.

The area within which the mammal reacts behaviorally or physiologically to a sound is the zone of responsiveness⁸¹. The zone of masking is the area within which a sound is robust enough to interfere with detection of other sounds⁸². Communication calls and other natural sounds emitted by marine mammals are masked by human-generated sound under some conditions. Low-frequency sounds are more likely to affect the detection of communication calls, because they, too, tend to be at lower-frequencies⁸³. The closest zone to the sound source—the zone of hearing loss, discomfort, or injury—is the area where in the received sound level is high enough to cause discomfort or tissue damage to auditory or other systems⁸⁴.

⁸⁰ Richardson et al., *Marine Mammals and Noise*, 326-381.

⁸¹ Ibid.

⁸² Ibid.

⁸³ Ibid.

⁸⁴ Ibid.

Spatial Zones of Noise Influence

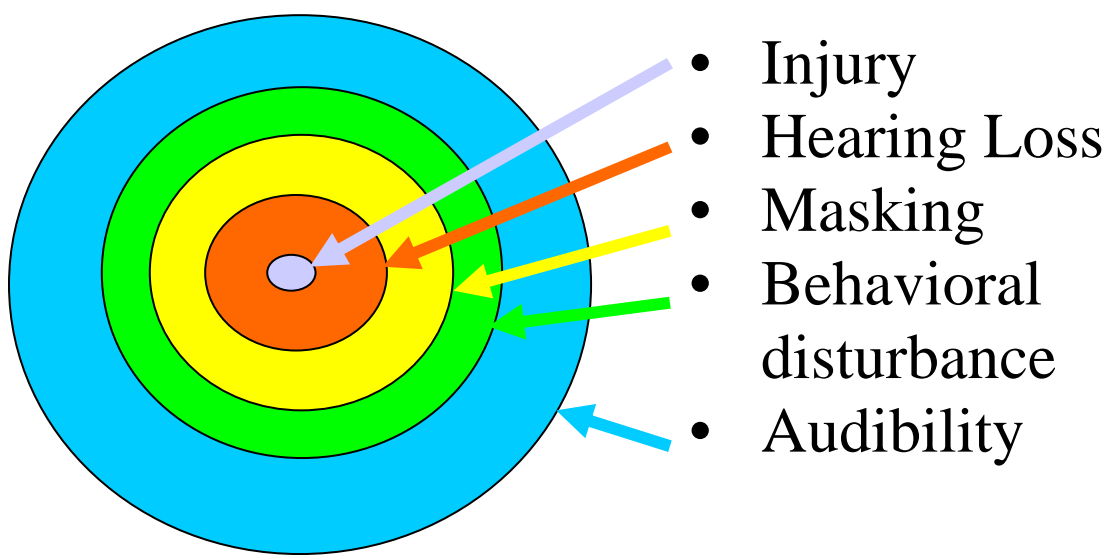


Figure 3: Spatial Zones of Noise Influence. Simplified model because doesn't always propagate in a sphere. Adapted from Richardson et. al., 1995.

8 CONCLUSION

“To fully address the adverse effects of noise on the marine environment, it will also be necessary to look at the long-term impact on species, ecosystems and habitats. Appreciating this, acoustic pollution in the marine environment is clearly an issue whose solution remains to be found in the coming decades.”

Doltinga and Elferink, 2000

Each year the seas grow noisier, and each year our global investment in shipping and sonar and other intrusive technologies becomes more entrenched. If these trends

continue unchecked, then sometime in the next century we are likely to witness several collisions between human economics and marine ecology that may prove costly for both.

Fortunately, the issue of human-generated noise and marine mammals has been gaining the attention of scientists, conservationist, and policy makers. With the help of the National Oceanic and Atmospheric Administration (NOAA), The American Zoo and Aquarium Association (AZA), Consortium for Oceanographic Research and Education (CORE) and the Marine Mammal Commission (MMC), the general public is becoming aware and getting involved.

The scientific community faces an increasing call to advocacy and outreach in solving the problem of ocean noise. The brochures, which will be distributed at the lectures, are one small response to this call. Providing public education and outreach is an effective way to increase awareness and to improve the conservation of the ocean and its inhabitants.

Every breath we take is dependent on the ocean. Unless we really understand how that vast system works, and take better care of it, it isn't just the ocean that's in jeopardy. Our whole future is at stake.

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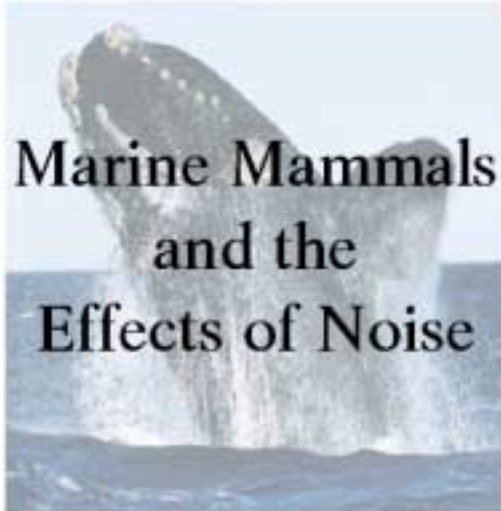
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APPENDIX 1

Brochure 1: For the Scientific Community



Marine Mammals and the Effects of Noise



*Facts about acoustic signals
and potential impacts of
human sound sources*

Educational series sponsored by:



MARINE MAMMALS USE SOUND

Marine mammals obtain a range of information about their environment by listening to the sound from many natural sources, aside from using sound to communicate with members of their own species and sense their environment. Like almost all animals who live under water, they rely on hearing much as people rely on sight to carry out their primary life functions.



NAVIGATION

Mysticete whales may use low frequency calls to orientate themselves underwater in certain conditions.

COMMUNICATION

All marine mammals appear to produce sounds when interacting socially. Some of these sounds, such as those produced between mothers and young and between rival males, play essential functions in reproductive biology.

PREDATOR AVOIDANCE

Whales may use passive listening to locate and avoid predators such as sharks and other marine mammals. Killer whales have figured this out and therefore hunt silently.

PREY DETECTION

Marine mammals may listen to the sounds their prey make and eavesdrop to find food. Cetaceans use a form of underwater sonar called echolocation to focus sound on prey to locate them.



Human-Generated Noise

HUMAN ACTIVITIES

Sounds from many different human sources are increasingly being produced in the marine environment. These sounds are produced either on purpose or as a by-product of some other activity. Humans intentionally produce sound to visualize the underwater world when using such tools as sonar systems, oceanographic research vessels, and seismic sounds for finding offshore oil deposits. People also produce sound unintentionally in conjunction with various commercial activities such as shipping, drilling and marine construction.

CONCERNS

As overall noise levels increase in some areas of the ocean, scientists, conservationists, federal agencies, and the general public are becoming increasingly concerned about the potential impact of sound on marine mammals. Concerns include whether human-generated sounds may interfere with normal uses of sound or directly cause marine mammals physical harm.

POTENTIAL IMPACTS OF HUMAN NOISE

Over the past decade, scientists have begun to realize that the sounds humans emit into the ocean have significant effects on the behavior and hearing systems of marine mammals. A number of factors determine the effect a specific sound may have on a marine mammal such as the sound level, hearing ability or behavioral state of the animal, and physical properties of the underwater environment.



Potential Impacts

DISRUPTION OF NORMAL BEHAVIOR

While behavioral reactions may be extreme as in the case of strandings, animals can become accustomed ("habituated") to the presence of noise. Noise may have other effects on hearing.

INTERFERENCE WITH COMMUNICATION

Masking occurs when there is a decrease in the mammal's ability to detect relevant sounds in the presence of other sounds because both the signal and the masking noise have comparable frequencies and amplitudes at the same time. This may have significant effects on important biological functions.

HEARING LOSS

Exposure to persistent noise may result in their temporary or permanent hearing loss. This level of hearing may be severely debilitating.



Critical Research Needs

MEASURING NOISE IN THE OCEAN

- Amazingly little is known about how much ambient noise humans contribute in various ocean areas and how this changes over time
- It would be beneficial to develop a passive acoustic monitoring network to understand natural systems

MARINE MAMMAL DISTRIBUTION/ECOLOGY

- Research and gather information on marine mammal's natural use of sound and how animals cope with exposure to human-generated noise
- Use passive detection of vocalizing animals to determine the distribution of marine mammals and their movement patterns

IMPACTS OF NOISE ON MARINE MAMMALS

- Discover how noise impacts marine mammal hearing and behavior
- Improve techniques to obtain hearing data for more species and individual marine mammals
- Examine the cumulative impacts of chronically present noise on marine mammals
- Develop a global marine noise monitoring system for continuous and intermittent noise sources for a variety of habitats





STAY INFORMED

Seek information on marine noise issues from a variety of sources, particularly those based on scientific research.

STAY ENGAGED

Participate in the increasingly numerous workshops and meetings on noise issues and make constructive contributions.

SUPPORT RESEARCH

Support funding for research aimed at addressing the most pressing data needs, such as measuring trends in marine noise and understanding why certain marine mammals strand in the presence of some sound sources.

SUPPORT TECHNOLOGY

Support the development of technologies that minimize incidental noise in the ocean, such as quieter forms of marine transportation and shipping.

FOR MORE INFORMATION

In the Library

- *Marine Mammals and Noise* by W. John Richardson *et al.*, 1993.
- *Ocean Noise and Marine Mammals* by the National Research Council, 2002.

On the Web

- National Academy of Science's Sounding Out the Ocean's Secrets www.beyonddiscovery.org/content/view/article.asp?id=219
- NOAA Fisheries Office of Protected Resources Acoustics Program www.nmfs.noaa.gov/pr/acoustics/
- Marine Mammal Commission-Sound Program www.mmc.gov/sound/

APPENDIX 2

Brochure 2: For the General Public



Marine Mammals and the Effects of Noise

*Facts about acoustic signals and
potential impacts of human
sound sources*



Educational Series Sponsored By:



MARINE MAMMALS USE SOUND

Marine mammals rely on hearing much as people rely on sight to carry out their primary life functions.

Many marine mammals use sound for:

- Navigation
- Communication
- Predator Avoidance
- Prey Detection



Marine Mammals

NAVIGATION

Baleen whales may use low frequency calls to orientate themselves underwater in certain conditions.

COMMUNICATION

All marine mammals appear to produce sounds when interacting socially. Some of these sounds, such as those produced between mothers and young and between rival males, play essential functions in reproductive biology.

PREDATOR AVOIDANCE

Whales may use passive listening to locate and avoid predators such as sharks and other marine mammals. Killer whales have figured this out and therefore hunt silently.

PREY DETECTION

Marine mammals may listen to the sounds their prey make and eavesdrop to find food. Toothed whales use a form of underwater sonar called echolocation to focus sound on prey to locate them.



Human-Generated Noise

HUMAN ACTIVITIES

Sounds from many different human sources are increasingly being produced in the marine environment. These sounds are produced either on purpose or as a by-product of some other activity. The following activities introduce sound into the ocean:

- Oil and gas exploration and extraction
- Ocean experiments
- Shipping
- Naval activities
- Coastal construction and development
- Seismic surveys

CONCERNS

As overall noise levels increase in some areas of the ocean, scientists, conservationists, federal agencies, and the general public are becoming increasingly concerned about the potential impact of sound on marine mammals. Concerns include whether human-generated sounds may interfere with normal uses of sound or directly cause marine mammals physical harm.



Potential Impacts

POTENTIAL IMPACTS OF HUMAN NOISE

A number of factors affect the response of marine mammals to sound in their environment: the sound level, physical and behavioral state of the animal, the acoustic characteristics, and ecological features of the environment in which the animal encounters the sound.

- Some potential impacts include:
- Disruption of animal behavior
 - Interference with communication
 - Hearing loss

DISRUPTION OF NORMAL BEHAVIOR

While behavioral reactions may be extreme as in the case of strandings, animals can become accustomed ("habituated") to the presence of noise. Noise may have other effects on hearing.

INTERFERENCE WITH COMMUNICATION

Masking occurs when there is a decrease in the animal's ability to detect relevant sounds in the presence of other sounds because both the signal and the masking noise have comparable frequencies and abide at the same time. This may have significant effects on important biological functions.

HEARING LOSS

Exposure to persistent noise may result in their temporary or permanent hearing loss. This loss of hearing may be seriously debilitating.



MEASURING NOISE IN THE OCEAN

- Amazingly little is known about how much ambient noise humans contribute in various ocean areas and how this changes over time
- It would be beneficial to develop a passive acoustic monitoring network to understand natural systems

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- Research and gather information on marine mammal's natural use of sound and how animals cope with exposure to human-generated noise
- Use passive detection of vocalizing animals to determine the distribution of marine mammals and their movement patterns

IMPACTS OF NOISE ON MARINE MAMMALS

- Discover how noise impacts marine mammal hearing and behavior
- Improve techniques to obtain hearing data for more species and individual marine mammals
- Evaluate the cumulative impacts of chronically present noise on marine mammals
- Develop a global marine noise monitoring system for continuous and intermittent noise sources for a variety of habitats



Critical Research Needs



YOU Can Make a Difference

STAY INFORMED

Seek information on marine noise issues from a variety of sources, particularly those based on scientific research.

STAY ENGAGED

Participate in the increasingly numerous workshops and meetings on noise issues and make constructive contributions.

SUPPORT RESEARCH

Support funding for research aimed at addressing the most pressing data needs, such as measuring trends in marine noise and understanding why certain marine mammals strand in the presence of some sound sources.

SUPPORT TECHNOLOGY

Support the development of technologies that minimize incidental noise in the ocean, such as quieter forms of marine transportation and shipping.

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- Marine Mammal Commission-Sound Program www.mmc.gov/sound/